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HIGH-ALTITUDE AREA NAVIGATION (RNAV) ENROUTE SIMULATION

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Mark R. Taylor

DECEMBER 1977

FINAL REPORT

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NOTICE

METRIC CONVERSION FACTORS

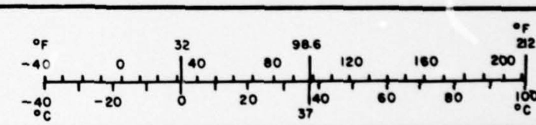
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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16. Abstract

A four-part dynamic simulation using two systems of navigation, area navigation (RNAV) and very high frequency omnidirectional radio range (VOR), was conducted using the Digital Simulation Facility (DSF) at the National Aviation Facilities Experimental Center (NAFEC). The objectives were to: (1) validate the results derived from fast-time simulation tests of RNAV and Jet-VOR route structures through real-time simulation tests, (2) determine whether benefits resulted from the application of RNAV in the high-altitude enroute environment, and (3) establish the impact that the number of potential aircraft conflict situations has on the ATC system and system user. Simulations were conducted in a fast-time mode, without controller intervention, for an area encompassed by five high-altitude Chicago Air Route Traffic Control Center (ARTCC) sectors and for a single selected sector of the five. Real-time simulations, with controller intervention, were conducted for both the five- and one-sector configurations. Test results showed that there was a significant reduction in controller workload in the RNAV system compared to the VOR system for both sector configurations, and that correlation was found to exist between the Lincoln Laboratory and NAFEC fast-time simulation potential conflict data. Comparison of the fast-time potential conflict data with real-time controller workload and system performance measures did not show any correlation between the two sets of data. The data from the real-time simulations showed major variations between runs of the same traffic sample, thus precluding the isolation of any possible impact from variations in number of potential conflicts.

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PREFACE

The authors wish to express their appreciation to the personnel of the System Software Section for their sustained efforts; in particular, Mr. Louis J. Bona, chief, for his timely management of the computer program requirements; Mr. Ralph G. Wilson, Jr., for his supervision of the software work required for software modifications and new programs; Mrs. Mary L. Cale, and Messrs. Stanley R. Pszczolkowski and John DiNofrio for their programming support during the conduct of these tests; Mr. Richard Algeo for reduction of the Lincoln Laboratory's data tapes and data reduction of the test runs; and Ms. Josephine Pitale for her software work in plotting the data for the various maps.

Appreciation is also conveyed to the personnel of the Data Preparation Section for their work in preparing the Link-1 data and writing the numerous controllers' flight progress strips and scripts; Mrs. Doris M. Westervelt, chief, for her supervision and effective assignment of personnel in support of this project; and Mrs. Iva Callio for her tireless efforts accounting for the many traffic samples and data for the Link-1 programs required by the RNAV and Jet-VOR route structures.

Finally, sincere thanks are accorded to Messrs. Thomas E. Morgan, Jr., and Edward H. Stevens of the Computer Sciences Corporation who prepared the test design, selected and performed the statistical tests and analyses, and wrote the traffic sample software.

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INTRODUCTION

PURPOSE.

The general purpose of this simulation was to appraise the merits of fast-time simulation tests with real-time simulation tests in a high-altitude enroute air traffic control center (ARTCC) environment. The specific simulation objectives were:

1. To corroborate, enforce, and/or qualify the results derived from fast-time simulation tests of area navigation (RNAV) and Jet-VOR (very high frequency omnidirectional radio range) route structures through real-time simulation tests.

2. To determine whether or not system benefits and/or impact may result from the application of RNAV in the high-altitude enroute environment.

3. To establish the impact that the number of potential aircraft conflict situations found in fast-time simulations (of given traffic samples, route structures, and geographic areas in which controller intervention is not introduced) has on the following components when the same conditions (traffic samples, route structures, and geographic areas) are simulated in real-time with controller intervention: system capacity, controller workload, and user benefits.

BACKGROUND.

The term, area navigation (RNAV), specifies a method of navigation that permits aircraft operations on any desired course within the coverage of station-reference navigation signals or within the limits of self-contained system capability (Federal Air Regulations (FAR), Part 1).

The initial studies of high-altitude enroute applications of RNAV routes used data generated by Lincoln Laboratory, Bedford, Massachusetts. These studies were conducted in a fast-time simulation mode. Their results indicated that the use of RNAV had a significant advantage for both user and air traffic control systems in terms of reduced potential conflicts. Since these tests were in a fast-time mode, controller intervention was not simulated. Therefore, it was determined that an air traffic control (ATC) real-time simulation which included controller intervention was required to calibrate the fast-time simulation results.

The Area Navigation Program Plan, FAA-ED-04-02, September 1974, described the research and development efforts required in support of the FAA/Industry Area Navigation Task Force Report, February 1973. The research and development efforts included a series of real-time ATC simulation tests which would extend over a period of several years. An outgrowth of the simulation studies would be the comparison of fast- and real-time simulation results. The resultant comparison would serve to validate the results of previous fast-time studies.

DISCUSSION

GENERAL.

The use of RNAV and Jet-VOR route structures in an ARTCC's area was tested in simulation at the National Aviation Facilities Experimental Center (NAFEC) Atlantic City, New Jersey. The tests used the Digital Simulation Facility (DSF) to obtain both fast- and real-time simulation results. The fast-time tests were performed in a nonintervention mode (without controller intervention), while the real-time tests incorporated controller intervention capabilities.

For both the fast-time and real-time simulations, two configurations were used. The first configuration consisted of five sectors approximating the areas and contours of five high-altitude sectors of the Chicago ARTCC as shown in figure 1. The sectors are identified as sectors 9, 13, 14, 28, and 29. The second configuration consisted of sector 28 only. These sectors were selected for simulations due to the wide range in potential conflicts detected in the previous Lincoln Laboratory fast-time simulations.

Care was taken in the development of traffic samples (including such considerations as aircraft type and performance, cruise altitude, and volume) to insure, to the highest degree possible, that both RNAV and VOR system traffic were the same as that which entered or departed from these selected sectors during the previous Lincoln Laboratory tests. In addition, VOR routes, direct flightpaths, RNAV routes, and distribution of traffic over the routes used in the NAFEC simulations duplicated, to the maximum extent possible, the conditions simulated by Lincoln Laboratory. To insure this compatibility, traffic sample and route structure data previously stored on computer tape for use by Lincoln Laboratory were extracted and processed for the NAFEC simulations. (Refer to appendix A.)

Two conditions were tested in the fast- and real-time simulations of both the five- and one-sector configurations. Under one condition, all traffic flew via the Jet-VOR routes and direct flightpaths shown in figures 2 and 4. Under the other condition, all traffic flew via the RNAV routes shown in figures 3 and 5 with a few exceptions. These exceptions were caused by the RNAV structure used.

The RNAV structure was designed by NAFEC previously for use in a study of RNAV route design concepts and was one of a series used at Lincoln Laboratory in their fast-time simulations (reference 1). This RNAV design was not intended to accommodate traffic between all city pairs. While all major traffic flows were accommodated by the RNAV structure, there was a limited number of flights between some city pairs for which RNAV routes were not considered in the design. To accommodate this traffic in both the Lincoln Laboratory and NAFEC simulations, certain Jet-VOR and direct routes were retained, and all other non-RNAV routes were deleted under simulation of the "100-percent" RNAV condition.

TEST BED.

GENERAL. RNAV and Jet-VOR traffic density reduced from Lincoln Laboratory tapes were inputs to the DSF computer's programs for both fast-time and real-time tests. The DSF target generator caused these aircraft to fly in accordance with the stored flight plan data and aircraft performance characteristics. In the real-time tests, the air traffic controller could modify the aircraft's flight through a communication link between the DSF pilots and the controllers. Keyboard entries by the DSF pilots provided the response to the control instructions in the real-time simulation tests. In the fast-time simulations, no controller intervention (instructions) was used.

DIGITAL SIMULATION FACILITY. The components of the DSF used were: (1) the Sigma-5 computer, (2) DSF pilots' displays and keyboards with associated mini-computer, Alpha-16, and (3) controllers' digital displays, keypack, and communications. The Sigma-5 used the following computer programs:

Link-1: geographical area with routes, fixes, radar map, operational radar, and aircraft profiles by category.

Link-2: display aircraft position with data block on digital display at associated tube by control position, record number and type of controller and pilot keyboard inputs to be acted on and number and length of each radio or interphone contact by control position, aircraft position (x,y), and status, as IN or OUT of problem, climb or descent, speed, etc.

Link-3: data reduction of recorded information required for analysis.

The Sigma-5 computer was used for both fast- and real-time simulation tests. With the exception of pilot and controller keyboard messages and communication, duplicate data were recorded in both time modes. Link-3 programs were usually run on the Sigma-8 computer (see figure 6).

PILOTS AND DISPLAYS. Twenty pilot positions (figure 7) were required for the real-time tests for the five-sector simulation, and nine for the one-sector simulation tests. All aircraft operating within the test area were under ATC control in the real time tests. Fast-time tests did not require DSF pilots or controllers.

The pilot display contained the aircraft's identification, current altitude, and indicated airspeed and heading. Additional information, i.e., type of RNAV equipment, such as high or low category and distance to descent point, was added to the display. The pilot could, through the keyboard, display assigned altitude when climbing or descending. This was done so that departure flights, when transferred to the sector of interest, would report: "Leaving flight level 180 for flight level 350," which aided the controller's radar identification.

AIR TRAFFIC CONTROL POSITIONS. The DSF control laboratory (figure 8) was configured to simulate five high-altitude control sectors in the initial tests and one sector in the final tests of a National Airspace System (NAS) enroute center. The test area was supported by support sectors and a terminal area support position. These support areas were manned by air traffic controllers whose duties were to give and receive handoffs to and from the test sectors and insure that aircraft entering the test area were separated prior to the handoff.

Associated with each coordinator, radar, and support controller position was a slew ball, keypack, radio transmitter and receiver lines with speaker and headset selection, and interphone lines to the other control positions. The manual controller position equipment consisted of interphone lines and flight progress strips.

RADAR DISPLAYS AND DATA BLOCKS. The five-sector tests required eight simulated digital radar displays, and the one-sector tests required four simulated digital radar displays to accommodate the test sector(s) and support areas.

Associated with each aircraft's radar target was a data block. The data block contained the aircraft's identification, with the letter "R" added to the end of the identification to designate RNAV-equipped aircraft. The second line of the data block contained the assigned altitude of the aircraft and the current altitude of the aircraft. Between the assigned and current altitude, an up or down arrow was displayed to indicate when the aircraft was climbing or descending, or a plus or minus sign to indicate the aircraft was above or below assigned altitude.

FLIGHT PROGRESS STRIPS. A flight progress strip was posted in each test sector for each aircraft flight. Support sectors and terminal area were provided with scripts listed on program sheets. The strips and scripts information contained aircraft's identification, type of aircraft and groundspeed, assigned or requested altitude, and point of departure and arrival with associated route information.

In the five-sector tests, the controllers were also provided with an alphabetized script, because the strips were not readily available from the adjacent bays. In the one-sector tests, the manual controller kept current strips in front of the radar controller.

FIX AND ROUTE NOMENCLATURE. Fixes were identified by the five test sectors identification. The test sectors were designated clockwise from the southern sector (13), A, B, C, D, and E. Fixes within the test sectors were designated by the sector's letter and number and fixes in the support area were assigned two-letter identification, with the first letter being that of the adjacent test sector. The exceptions were navigation aides (VOR's) and airports, which were assigned their published identification.

Routes were identified by consecutive fixes with no route designation.

The above methods of fix and route identification were used to facilitate the area checkout of each controller. Depicted on the radar map were intersections of routes and start points with their identification. Approach fix identification and route centerlines were not depicted on the radar map to reduce clutter.

CONTROLLERS' LABORATORY CONFIGURATION. Shown in figure 9 are the laboratory configuration and controller's operating positions. Two control positions were associated with each radar display and identified by display number. Each control position had a keypack to control data block information, receive and make handoffs, and point out aircraft to other control positions.

TEST DESIGN.

GROUND RULES. The following ground rules governed the conduct of the tests:

(1) Only aircraft operating under instrument flight rules (IFR) were simulated.

(2) Radar separation minima were in accordance with Stage A digitized (narrowband) radar systems.

(3) Traffic entering or leaving the controller's area of jurisdiction was separated by the transferring controller prior to handoff.

(4) Aircraft on vectors or RNAV offset were coordinated with the receiving controller.

(5) All aircraft simulated had operating 4096 beacon transponder equipment with automatic altitude reporting.

(6) Adequate radar, communication, and navigation aids coverage existed at all times in the area simulated.

(7) The traffic density reduced from the Lincoln Laboratory's data tapes supported the simulation test objectives.

(8) Data reduction programs determined when the aircraft was in the test sector and only these data were used for fast- and real-time analysis.

GEOGRAPHY. The areas simulated covered an area of approximately 500 by 300 nmi for the five-sector tests and 255 by 120 nmi for the one-sector tests. Figures 2 through 5 show the simulated area with associated routes used for both simulation of the Jet-VOR and RNAV systems. As previously mentioned, some of the VOR routes were retained for simulation of the RNAV environment to insure that routes were available for all traffic simulated, since the RNAV route structure design simulated provided routes serving only major traffic flows, representing the major portion of the total traffic. The Jet-VOR route structure shown in figures 2 and 4 includes charted Jet-VOR routes, transition, and direct flightpaths. The RNAV structure shown in figures 3 and 5 depicts the RNAV structure simulated, including transition routes that would normally not be depicted on an airway chart. Therefore,

the reader is cautioned that these illustrations of both the Jet-VOR structure and RNAV structure represent flightpaths rather than charted airways. In the fast-time simulations, flights flew via the flightpaths illustrated. In the real-time simulations, flights were initially cleared via the paths depicted, but as the result of controller intervention, the flightpaths could be modified by radar vectors, parallel offsets, or other forms of rerouting.

A terminal support area controlled flights departing the Chicago terminal area. Departures were released to the high-altitude sectors approximately 45 nmi from the center of the terminal area, usually below 18,000 feet. Arrival flights were released to the terminal controller at the appropriate approach fix at 17,000 feet or above. Boundaries for the support sectors were the adjacent test sector boundary.

TRAFFIC SAMPLES. A master traffic sample was developed duplicating to the highest degree possible that portion of the Lincoln Laboratory traffic sample (per the year 1977) that impacted on the areas to be simulated in real-time. By randomizing the start times for aircraft entering the simulated sectors, 20 additional traffic samples were developed. All 21 RNAV samples were simulated in fast-time and an initial selection was made based on the data. Only those Jet-VOR samples corresponding to the best RNAV runs were made. The selection of samples was based on obtaining a wide and uniform spread in the numbers of potential conflicts for each sector for both the RNAV and Jet-VOR samples. The number of potential conflicts (instances in which less than minimum standard separation existed) within each sector was recorded as shown in table 1.

Potential conflicts are violations of standard ATC separation criteria which occur during uncontrolled (fast-time) simulation tests. These conflicts are considered "potential conflicts" in the sense that in a controlled situation, action could be taken to prevent the violation. Standard radar separation criteria were used in accordance with the Air Traffic Control handbook 8110.65, dated January 1, 1976 (reference 2). Basically this criteria requires that flights below 60,000 feet (FL 600) and 40 nmi or more from the radar antenna be separated by a minimum of 5 nmi unless vertical separation is provided (i.e., 1,000 feet at and below 29,000 feet (FL 290), and 2,000 feet above 29,000 feet).

A flight level is an altitude level of constant atmospheric pressure related to a reference datum of 29.92 inches of mercury. Each is stated in three digits representing hundreds of feet. For example, FL 250 represents a barometric altimeter indication of 25,000 feet (FAR Part 1). For the purpose of these tests, potential conflicts were recorded at and above 17,000 feet, the high-altitude stratum starts at FL 180.

Eight traffic samples were selected for real-time simulation of the five-sector configuration, and subsequently three of these samples were used in the one-sector configuration tests as shown in table 2. Table 2 also shows the density of aircraft within the 2-hour simulated period varies between samples, due to the effect of randomized start times, and between the RNAV and VOR systems as the result of the difference of the routes and sectors

TABLE 1. POTENTIAL CONFLICTS BY SAMPLE NUMBER

		Sample Number																				
Route	Sector	M	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
	9	2	4	4	1	1	1	4	3	2	1	3	1	3	3	1	2	2	2	2	1	3
	28	7	4	5	8	5	9	8	7	6	4	3	8	9	6	8	6	2	8	6	7	6
RNAV	29	5	6	3	3	5	3	1	4	2	6	3	8	3	3	5	8	3	5	1	5	2
	14	4	4	2	3	3	3	7	4	4	3	4	5	2	2	1	1	5	5	0	0	4
	13	4	4	5	6	5	3	2	1	2	6	3	4	5	2	0	3	4	4	3	8	3
	9		4	2				2	2		1	0		2			3	2	2		3	
	28		10	22				27	13		22	18		23			21	18	18		24	
VOR	29		5	5				6	3		5	4		6			6	3	3		5	
	14		11	12				19	8		12	12		15			17	18	11		11	
	13		3	3				4	1		6	5		3			3	3	3		6	

TABLE 2. AIRCRAFT DENSITY BY SECTOR

2-hour Data Period
Five-Sector Tests
Samples

Sector	Systems	2	6	7	9	10	15	17	19
9	RNAV	46	43	46	56	57	58	58	54
	VOR	45	58	49	46	47	47	48	45
28	RNAV	69	69	68	76	79	78	79	80
	VOR	93	92	70	92	92	93	93	88
29	RNAV	72	72	72	80	85	85	81	82
	VOR	69	67	70	67	64	68	65	69
14	RNAV	50	50	52	61	57	62	61	60
	VOR	68	69	70	69	69	70	71	69
13	RNAV	97	98	99	101	102	104	101	101
	VOR	93	93	93	91	94	93	90	94

One-Sector Tests

Sector	Systems	1	6	10
28	RNAV	63	63	63
	VOR	69	70	69

TABLE 3. POTENTIAL CONFLICTS--SECTOR 28, ONE-SECTOR TESTS

Sample Number

System	1	6	10
RNAV	4	8	3
Jet-VOR	10	27	18

penetrated by these routes. It should also be noted that in the one-sector configuration (using sector 28 only), the aircraft density within sector 28 in the one-sector tests is less in all three traffic samples than is shown for the same sector and traffic samples in the five-sector configuration. This was the result of the deletion of those flights simulated in the five-sector tests that only cut across a corner of sector 28 and had minimum impact on controller workload and did not affect the conflict count shown in table 1 and table 3. (See appendix B and table B-1, for traffic sample composition and matrices.)

Shown in table 4 is the total number of aircraft that entered the test's area during the 2-hour data collection period for the fast-time simulation of the five- and one-sector configurations.

TABLE 4. AIRCRAFT DENSITY--FAST-TIME

2-Hour Data Period by System and Sample

Systems	Five Sectors Tests Samples							
	2	6	7	9	10	15	17	19
RNAV	280	275	277	275	273	279	274	281
Jet-VOR	277	275	279	274	273	277	275	276

Systems	One Sector Tests Samples		
	1	6	10
RNAV	63	63	63
Jet-VOR	69	70	69

<u>CONTROLLER PROCEDURES</u>. Standard ATC procedures were applied as stated in handbook 7110.65 (reference 2), and RNAV procedures and phraseology were used as applicable. Controllers were instructed to provide ATC and related services to all aircraft under their jurisdiction.

Departures from the same airport were separated by a minimum of 32 seconds as provided by the basic data. Departure control separated aircraft prior to reaching 17,000 feet. No separation was given below 17,000 feet to insure as much duplication of the fast-time runs as possible.

Support sectors provided separation only at the sector boundary for aircraft entering the sector of interest. As long as the aircraft were separated at the boundary, no action was taken by the support sector unless requested by the test sector controller. This was to insure that potential conflicts identified from fast-time runs would be duplicated to the extent possible in the real-time runs of the sector(s) of interest.

Further restrictions to the sector-of-interest controller was the limitation of arrival aircraft remaining at altitude until a request for descent was received from the aircraft. This was done to duplicate the fast-time runs, and

to determine the impact of controller's intervention on altitude assignment and restrictions. This procedure was introduced only in the one-sector configuration. DSF pilots were instructed to refuse descent clearance from cruise altitude until within 30 nmi of descent point or request clearance when within 10 nmi of descent point.

The descent point was a point at which arrival aircraft would start a descent to cross the arrival fix at 17,000 feet. The descent point was determined by the aircraft's descent rate and groundspeed. The point would differ by aircraft category and flight plan true airspeed.

Another restriction to the sector-of-interest controller was the use of speed restriction which pilots refused if their aircraft was at or above FL 290.

All aircraft cleared off of filed flight plan route were coordinated with the support or sector-of-interest controller prior to transfer of control.

PILOT PROCEDURES. Prior to the laboratory tests, the DSF pilots received a detailed briefing on the purpose and objectives of the simulation. They were given material which defined their expected inputs and responses to control instruction. The tests for five sectors required 20 pilots, and 9 pilots were required for the one-sector tests.

TRAINING. Controller and pilot training started March 29, 1976, and continued to April 20, 1976. During this time, controllers were checked out on two control positions using the master sample for traffic input for both the Jet-VOR and RNAV systems. A refresher training period was given for one-sector tests.

TEST MATRIX. The simulation was planned to provide statistical results from both fast- and real-time simulation of both systems: Jet-VOR and high-altitude RNAV routes.

The test was divided into four parts for both the five- and one-sector configurations:

Part 1 Jet-VOR aircraft without controller intervention,

Part 2 RNAV aircraft without controller intervention,

Part 3 Jet-VOR aircraft with controller intervention, and

Part 4 RNAV aircraft with controller intervention.

It was anticipated that more potential conflicts would result in part 1 than in part 2, based upon previous Lincoln Laboratory fast-time simulation results.

The four parts provided a basis for the following statistical comparisons:

1. The number of potential conflicts between aircraft using Jet-VOR routes for comparison with potential conflicts between aircraft using RNAV routes,

2. The number of potential conflicts versus controller workload,

3. A basis to determine the effect on controller's workload and user impact as a function of controller intervention under conditions in which known numbers of potential conflicts were given.

4. Compare controller workload and system user impact between RNAV and Jet-VOR systems.

Shown in table 5 is the test design for the number of data runs for the five-sector tests.

TABLE 5. TEST DESIGN--FIVE SECTORS, NUMBER OF DATA RUNS

	JET-VOR		RNAV	
Sample	Fast-Time	Real-Time	Fast-Time	Real-Time
2	1	2	1	2
6	1	2	1	2
7	1	2	1	2
9	1	2	1	2
10	1	2	1	2
15	1	2	1	2
17	1	2	1	2
19	1	2	1	2
Total	8	16	8	16

Two controller teams were used in the five-sector configuration tests. Test controllers were assigned a sector under each team configuration. The order of runs by sample was RNAV, VOR, VOR, RNAV, RNAV, etc., for team A. For team B it was VOR RNAV, RNAV, VOR, VOR, etc. Team B was formed by randomly reassigning the controllers from team A to the various support and test sectors for their test runs. This type of assignment is comparable to ARTCC assignment practices.

Shown in table 6 is the test design for the number of data runs for the one-sector tests.

TABLE 6. TEST DESIGN--ONE SECTOR, NUMBER OF DATA RUNS

	Jet-VOR		RNAV	
Sample	Fast-Time	Real-Time	Fast-Time	Real-Time
1	1	4	1	4
6	1	4	1	4
10	1	4	1	4
Total	3	12	3	12

The one-sector design was four teams, three samples, and two systems. The run order by sample and system was duplicated for teams 1 - 2, and 3 - 4. Each team made one run per sample under each system, and each team completed all six runs prior to the next team tests. Teams 1 and 2 runs were Jet-VOR, followed by RNAV runs. Team 3 and 4 runs were RNAV, followed by Jet-VOR runs. The 24th data run was completed July 28, 1976.

DATA RUNS, REAL-TIME.

The purpose of the real-time runs was to correlate the resultant data with the base fast-time data. The problem with duplicating fast-time conflicts was controller reaction to these situations. Conflict conditions were eliminated by the controller giving offset or vectors to aircraft prior to the situation developing. The vector or offset would create a new route for the aircraft which bypassed the fast-time routing. Thus, duplication of potential conflicts in the real-time simulation was not possible. In many cases, a controller-assigned vector or offset or altitude restriction might resolve several potential conflicts on the one hand, but could also result in some other potential conflicts developing later that were not present in the fast-time simulation. This effect could not be isolated or analyzed in this simulation.

Data block clutter was a problem to the controllers. This was the result of data block size and the sector area displayed. As a result, controllers would clear an aircraft for a 5-nmi offset and the next aircraft for a 10-nmi offset to insure that data block overwrite would not occur. This action by the controller reduced the number of data block positioning messages and his workload. The same held true for vector clearances, in that aircraft on common routes were given vectors which paralled the filed route by 5 and 10 nmi, respectively.

The controllers were unreceptive to having aircraft remain on their filed route with potential conflict situations recurring. Instead, the controllers issued clearance which insured separation and reduced the number of control instructions for all potential conflict situations well prior to the condition occurring. This resulted in route modifications and altitude restrictions being imposed on flights that may not have been involved in a potential conflict if left to fly along the initially cleared route and no altitude restriction imposed. Departure and arrival aircraft were not cleared back to their filed route until requested or approach fix altitude was reached. If the requested or approach fix altitude was not available, the next available altitude was assigned, rather than have the aircraft remain on an offset or vector.

DATA COLLECTION. From the 3-hour simulation run, a 2-hour data period was recorded on magnetic tapes. The recording period was controlled by the computer program. The first hour of the simulation was used to load aircraft into the test area. The second hour was the start of the data collection period.

The data were analyzed by computer programs to determine when each aircraft was in the test sector and to provide measures of systems performance and controller workload. No analyses were made for aircraft outside of the test sector(s).

Shown in appendix C are the data that were recorded on magnetic tapes during the data collection period. From these data, the system measures were reduced.

MEASURES. The measurements reduced from fast- and real-time simulation data and analyses are defined as follows:

1. Potential Conflicts are the number of violations of conflict criteria. The number represents the number of occurrences and not the number of aircraft involved.

2. Time in System is the time in seconds that each aircraft was in the test area.

3. Distance Flown is the mileage in nautical miles that the aircraft flew in the test area.

4. Number of Aircraft Handled is a count of the number of aircraft that entered the test area.

5. Number of Push-to-Talk is a count of the number of controller-to-pilot radio transmissions made by the test controller(s).

6. Total Talk Time is the sum of all radio transmissions, in seconds, made by the test controller(s).

7. Average Contact Duration is the total talk time divided by the total of push-to-talk messages. The results are average radio contact duration per message in seconds.

8. Average Number of Contacts per Aircraft is the sum of the number of push-to-talks divided by the number of aircraft handled. The result is the average number of communications per aircraft controlled.

9. Average Talk Time per Aircraft is the total talk time divided by the number of aircraft handled. The results are average duration (seconds) of communications per aircraft controlled.

10. Number of Control Messages is the count of control messages to the pilot which would require a change in flight such as climb, speed, vector, offset, etc.

Listed in table 7 is the application of the measures under fast-time simulation and real-time simulation tests.

It was anticipated (for the purpose of correlation of fast- and real-time simulation results) that as the potential conflicts increased/decreased, there would be a correlation with controller workload and/or system impact.

TABLE 7. DATA MEASURES

Tests	
Fast-Time Simulation	Real-Time Simulation
Potential Conflicts	---
Time in System	Time in System
Distance Flown	Distance Flown
Number of Aircraft Handled	Number of Aircraft Handled
---	Number of Push-to-Talk
---	Total Talk Time
---	Average Contact Duration
---	Average Number of Contacts per Aircraft
---	Number of Control Messages
---	Average Talk Time per Aircraft

RESULTS

To determine whether differences existed between the test variables, the results of fast- and real-time simulation tests were subjected to statistical tests. The significance level was preestablished at $\alpha=.05$ for applicable tests. This 95-percent confidence level determined the acceptance or rejection of the null hypothesis that there is no difference between the tested measures.

FAST-TIME SIMULATION RESULTS.

COMPARISON OF LINCOLN LABORATORY DATA WITH FAST-TIME SIMULATION DATA. Fast-time simulations were made using 21 RNAV and 10 Jet-VOR samples in order to select a combination of 8 samples for real-time simulation which exhibited good statistical properties for the regression analyses to be conducted after the real-time runs.

The number of potential conflicts and average instantaneous traffic load (aircraft density per run) for each of the 21 fast-time runs was collected, and summary statistics were calculated as shown in tables 8 and 9, respectively. These data were subjected to a series of statistical tests employing the Students' t distribution which assumes a normally distributed parent population. A plot of the data for tables 8 and 9 showed that the plotted data do not produce a bell-shaped curve which a normal distribution would present. Since the statistical assumption of normality was not well satisfied, tests of the hypothesis using a t distribution were used which were insensitive to violations of the normality assumption; see reference 3, p. 305.

These data were compared with the 2-hour estimated potential conflict data from the Lincoln Laboratory simulations. The results of this comparison are given in table 10. As can be seen in that table, the results for the aggregate of the five sectors are in good agreement. However, for sector 13 for the Jet-VOR route structure, there are substantial differences between the Lincoln

TABLE 8. POTENTIAL CONFLICTS BY SAMPLE NUMBER AND STATISTICS

Route	Sector	Sample Number M	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Σ X	Σ X^2	Sample Average $\bar{X}$	Sample Variance S^2
	9	2	4	4	1	1	1	4	3	2	1	3	1	3	3	1	2	2	2	2	1	3	46	124	2.2	1.16
	28	7	6	5	8	5	9	9	7	6	4	3	8	9	6	8	6	2	8	6	7	6	135	941	6.4	3.66
RNAV	29	5	6	3	3	5	3	1	4	2	6	3	8	3	3	5	8	3	5	1	5	2	84	414	4.0	3.90
	14	4	4	2	3	3	3	7	4	4	3	4	5	2	2	1	1	5	5	0	0	4	66	270	3.1	3.13
	13	4	4	5	6	5	3	2	1	2	6	3	4	5	2	0	3	4	4	3	8	3	77	349	3.7	3.33
	Total	22	24	19	21	19	19	23	19	16	20	16	26	22	16	15	20	16	24	12	21	18	408	8168	19.4	12.06
	9		4	2				2	2		1	0		2			3		2		3		21	55	2.1	1.21
Jet-VOR	28		10	22				25	13		22	0		23			21		18		24		198	4132	19.8	23.51
	29		5	5				6	3		5	4		6			6		3		5		48	242	4.8	1.29
	14		11	12				19	8		12	12		15			17		18		11		135	1937	13.5	12.72
	13		3	3				4	1		6	5		3			3		3		6		37	159	3.7	2.46
	Total		33	44				56	27		46	41		49			50		44		49		439	19925	43.9	73.66

TABLE 9. AVERAGE INSTANTANEOUS AIRCRAFT LOAD PER RUN BY SAMPLE NUMBER

Route	Sector	Sample Number M	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Σ X	Σ X^2	Sample Average $\bar{X}$	Sample Variance S^2
	9	8.31	8.38	8.34	8.38	8.39	8.25	8.27	8.43	8.44	8.33	8.54	8.36	8.18	8.21	8.24	8.32	8.54	8.08	8.47	8.46	8.19	175.1	1460.1	8.3	.015
	28	9.62	9.38	9.15	9.52	9.90	9.54	9.85	9.60	9.73	9.33	9.89	9.56	9.92	9.56	9.63	9.67	9.33	9.55	9.76	9.66	9.32	201.5	1933.8	9.6	.045
RNAV	29	9.78	9.56	9.69	9.62	9.58	10.02	10.07	9.87	9.88	9.77	9.72	9.73	9.83	9.67	9.76	9.90	9.75	9.66	9.73	9.81	9.72	205.1	2003.9	9.8	.017
	14	7.52	7.55	7.18	7.63	7.51	7.68	7.54	7.36	7.45	7.35	7.19	7.47	7.61	7.55	7.56	7.49	7.26	7.45	7.44	7.41	7.38	156.6	1167.9	7.5	.019
	13	6.26	6.24	6.60	6.30	6.22	6.30	6.22	6.29	6.28	6.13	6.26	6.15	6.28	6.16	6.28	6.37	6.13	6.22	6.15	6.30	6.27	131.4	822.5	6.3	.011
	Total	41.49	41.11	40.96	41.45	41.60	41.79	41.95	41.55	41.78	40.91	41.60	41.27	41.82	41.15	41.47	41.75	40.99	40.96	41.55	41.64	40.88	869.7	36017.8	41.4	.116
	9		7.70	7.54				7.56	7.74		7.69	7.73		7.45			7.64		7.53		7.73		76.3	582.4	7.6	.011
	28		10.35	10.77				10.72	10.28		10.12	10.64		10.75			10.65		10.44		10.39		105.1	1105.3	10.5	.051
Jet-VOR	29		8.09	8.12				8.25	8.27		8.03	8.19		8.25			8.04		7.85		8.23		81.3	661.5	8.1	.018
	14		8.72	8.66				9.03	8.88		8.82	8.62		8.99			8.95		8.72		8.79		88.2	777.8	8.8	.020
	13		6.00	6.01				6.05	6.09		5.98	6.09		5.91			6.14		5.99		6.11		60.4	364.5	6.0	.006
	Total		40.86	41.10				41.61	41.26		40.64	41.27		41.35			41.42		40.53		41.25		411.3	16917.0	41.1	.120

TABLE 10. COMPARISON OF DSF AND LINCOLN LABORATORY (LL) POTENTIAL CONFLICT COUNTS IN FAST-TIME SIMULATION

System	Sector	DSF Average	DSF Variance	LL Estimate	Difference (LL-DSF)	t*	Significance Level $\alpha = .05$
	9	2.2	1.16	4.0	1.8	1.52	No
	28	6.4	3.66	8.6	2.2	1.05	No
RNAV	29	4.0	3.90	3.4	-0.6	0.27	No
	14	3.1	3.13	1.7	-1.4	.72	No
	13	3.7	3.33	2.9	- .8	.40	No
Total		19.4	12.06	20.5	.9	.29	No
	9	2.1	1.21	2.0	- .1	.08	No
	28	19.8	23.51	21.5	1.7	.32	No
VOR	29	4.8	1.29	3.0	-1.8	1.42	No
	14	13.5	12.72	5.5	-8.0	2.02	No
	13	3.7	2.46	8.0	4.3	2.47	Yes
Total		43.9	73.66	40.0	-3.9	.41	No

$$*t = \frac{\bar{X}_{DSF} - \hat{X}_{LL}}{S_1^2} \sqrt{\frac{N-1}{N+1}}$$

where

$\bar{X}_{DSF}$ = DSF average

$\hat{X}_{LL}$ = LL average

S_1^2 = Variance estimate

N = DSF sample size (21 for RNAV routes; 10 for Jet-VOR routes)

Laboratory estimates and the DSF fast-time results. These data were compared statistically to determine if the Lincoln Laboratory estimate could be considered a random sample from the distribution of DSF results. This test was derived (see appendix D) from a procedure described in reference 4 (w statistic page 489) for determining if two samples are from the same distribution. The results indicate that the Lincoln Laboratory estimates for Jet-VOR sector 13 were significantly different than the DSF results at the 5-percent level. Since the Lincoln Laboratory estimates were prepared by reducing the known 5-hour potential conflict count by a scaling factor estimated from the nationwide data, it is quite possible that these estimates are in error due to local (i.e., sector-by-sector) variations in that ratio. The close comparison of the aggregate data substantiates this conjecture, since that ratio would be more stable for larger subgroupings of the sectors.

RNAV VERSUS JET-VOR. A second series of tests was conducted to determine (1) if the number of potential conflicts which occurred using the Jet-VOR route structure was significantly greater than the number of potential conflicts which occurred using the RNAV structure, and (2) if the average aircraft load (aircraft density) was different when using the RNAV and Jet-VOR structures. The results of these tests are shown in tables 11 and 12, respectively. Since there are large differences in some of the sample variances, particularly for the potential conflict count, a procedure for handling two-sample tests with unequal variance developed by Walsh (1937) and documented in reference 5 (p. 299) was employed to determine statistical significance. As can be seen in table 11, the total conflict count across all sectors for the Jet-VOR runs was significantly greater than the count for the RNAV runs. This difference was created by very significant improvements for RNAV in sectors 28 and 14 and a marginal improvement in sector 29. (The mild advantage of the Jet-VOR structure in sector 9, was not statistically significant.)

In spite of great care in duplicating the flights and routes through both samples, the average aircraft load in the RNAV samples was significantly greater than in the VOR samples for the five-sector configuration. This difference, although not large (0.3 aircraft), is significant, due to the very small run-to-run variances (0.12 aircraft), and is probably caused by the fact that when viewed from the national level, certain flights may totally avoid the five key sectors. This effect is compounded by differences between the relative entry times of the aircraft into the five sectors in the Jet-VOR structure versus those entering the five sectors in the RNAV structure. These entry times were determined based on common airport departure times for both structures and subsequent transit time over the respective national structure used in the Lincoln Laboratory simulations. The different transit times cause different aircraft to be within the five key sectors during the 2-hour period selected. These effects are even more apparent on a sector-by-sector basis, where larger and more significant differences were observed.

The presence of significant differences in the average aircraft load data could complicate the analysis of the real-time results, particularly if the number of potential conflicts was dependent upon the load. To check for this dependence, several tests were performed. First, the correlation coefficient

TABLE 11. COMPARISON OF RNAV AND JET-VOR ROUTE STRUCTURES, POTENTIAL CONFLICT COUNT IN FAST-TIME SIMULATION

2 Sector	Number of Samples RNAV n_R	Number of Samples Jet-VOR n_V	Average Number of Potential Conflicts RNAV X_R	Average Number of Potential Conflicts Jet-VOR X_V	Sample Variance RNAV S^2_R	Sample Variance Jet-VOR S^2_V	Sample Statistic t	Degrees of Freedom d.f.	Significance Level (α)
9	21	10	2.2	2.1	1.16	1.21	-0.238	17.4	0.75
28	21	10	6.4	19.8	3.66	23.51	8.432	10.4	.999+
29	21	10	4.0	4.8	3.90	1.29	1.425	27.7	.914
14	21	10	3.1	13.5	3.13	12.72	8.724	11.2	.999+
13	21	10	3.7	3.7	3.33	2.46	0.000	20.5	.75
Total	21	10	19.4	43.9	12.06	73.66	8.694	10.4	.999+

TABLE 12. COMPARISON OF RNAV AND JET-VOR ROUTE STRUCTURES, AVERAGE AIRCRAFT LOAD IN FAST-TIME SIMULATION

Sector	Number of Samples RNAV n_R	Number of Samples Jet-VOR n_V	Average Aircraft Load RNAV X_R	Average Aircraft Load Jet-VOR X_V	Sample Variance RNAV S^2_R	Sample Variance Jet-VOR S^2_V	Test Statistic (t)	Degrees of Freedom (d.f.)	Significance Level (α)
9	21	10	8.3	7.6	0.015	0.011	-16.5	20.5	0.999+
28	21	10	9.6	10.5	.045	.51	10.6	16.8	.999+
29	21	10	9.8	8.1	.017	.018	-33.3	17.3	.999+
14	21	10	7.5	7.5	.019	.020	24.1	17.4	.999+
13	21	10	6.3	6.3	.011	.006	9.0	23.4	.999+
Total	21	10	41.4	41.1	.116	.120	2.25	17.8	.983

(reference 5, p. 217) was computed for each sector and for the total area for both structures. These values were tested for being significantly different than zero using the procedure described in reference 5, page 358. As shown in table 13, in no case was the correlation coefficient significant, indicating that within each sector, the variations in average load did not cause a related variation in potential conflicts. This lack of correlation, however, was probably caused by the small range of variation in the average traffic load. Therefore, the sector average values of the traffic load and potential conflict count were compared using Spearmans' Rank Correlation (reference 5, p. 424). This procedure yielded a correlation of 0.736 which is significant at the 0.98 level. Taken together, these two facts indicate that there is a relationship between traffic load and potential conflict count.

REAL-TIME SIMULATION RESULTS.

After completion of 20 data runs of the five-sector configuration, it was determined that the uncontrolled variables introduced in the simulation by controller intervention precluded collection of data for determination of any possible correlation between potential conflicts and controller workload and system user measures. It was determined, therefore, to discontinue the five-sector configuration prior to completion of the planned 32 tests and to start tests of the one-sector configuration. The 24 runs planned for the one-sector configuration were completed. However, even though the one-sector tests were closely monitored, the same problems generally existed in attempting to find any correlation between potential conflicts found in the fast-time simulation and the real-time simulation results.

Analysis of this experiment focused on the four fast-time measures and the nine real-time measures listed in table 7. The data measurements for the five-sector configuration are presented in table 14. For the single-sector configuration, the fast-time measurements are presented in table 15, and the real-time results are included as table 16. Because of a program error, it was not possible to obtain the fast-time measurements for the five-sector configuration as presented for the one-sector.

The expected results of the experiment were the following:

1. Comparison of user/system benefits/impact of the two ATC systems.

2. Correlation of fast-time and real-time simulation results.

3. Relationship of controller workload and system user impact to predetermined quantities of potential aircraft conflict situations.

The ATC system benefit comparisons were made on the data from the first 20 data runs (i.e., five sectors), and the correlation and potential conflict analyses were based on the single-sector data. The inclusion of five-sector tests was due to the fact that the RNAV and Jet-VOR route structures were balanced in the overall five-sector configuration; however, the routes were not balanced when the test area was reduced to a single sector. Because of the large run-to-run variation in the five-sector tests, it was virtually impossible to

TABLE 13. CORRELATION BETWEEN AVERAGE AIRCRAFT LOAD AND POTENTIAL CONFLICTS IN FAST-TIME SIMULATION

Sector	Structure RNAV	Jet-VOR
2	-0.0896	-0.0108
5	.2847	.4605
7	- .2205	.2744
9	- .0816	.4296
11	.0815	.0609
Total	- .0455	.3212
Critical Correlation Coefficient[1] = .10	.3700	.5490

[1]The significance of the correlation coefficient can be tested using the Students' t distribution using the following relationship:

$$t_{n-2,\ 1-\alpha/2} = \hat{p}\left(\frac{n-2}{1-\hat{p}^2}\right)^{1/2}$$

where:

$t_{n-2,\ 1-\ /2}$ = The tabulated Students' t value for n-2 degrees of freedom and a significance level of α for n, two-sided test of hypothesis

$\hat{p}$ = Sample correlation coefficient

n = Sample size

For a given sample size, this relationship can be inverted to provide a critical correlation coefficient. Values greater than this level are significant:

$$|\hat{p}_c| = \left(\frac{1}{(n-2+t^2)}\right)^{1/2}$$

TABLE 14. REAL-TIME DATA MEASUREMENTS FOR FIVE-SECTOR CONFIGURATION

Run No.	Sample No.	and Route Structure	Number of Aircraft Handled	Number of Push to Talk	Total Talk Time	Per Aircraft Average Contact Duration	Per Aircraft Average No. of Contacts	Per Aircraft Average Talk Time	Control Messages	Time in System	Distance Flown
1	6	RNAV	272	929	2975	3.2	3.4	10.9	993	287594	32405
2	6	Jet-VOR	271	1070	3271	3.1	3.9	12.1	1064	295643	33293
3	9	Jet-VOR	267	1013	3180	3.1	3.8	11.9	1078	282122	31810
4	9	RNAV	269	937	2916	3.1	2.5	10.9	961	284570	32405
5	10	RNAV	270	851	2651	3.0	3.2	9.8	831	279734	31805
6	10	Jet-VOR	270	983	2994	3.1	3.6	11.1	1027	295599	33569
7	2	Jet-VOR	274	934	2892	3.1	3.4	10.5	1000	287530	32507
8	2	RNAV	276	988	3220	3.3	3.6	11.7	927	286577	32360
9	15	RNAV	269	912	3086	3.4	3.4	11.5	983	284035	32175
10	15	Jet-VOR	274	1064	3447	3.3	3.9	12.6	1152	300131	33967
11	7	Jet-VOR	276	1103	3551	3.2	4.0	12.9	1175	299591	34014
12	7	RNAV	275	979	3050	3.1	3.6	11.1	1008	300269	33874
13	17	RNAV	271	898	3077	3.4	3.3	11.4	887	288025	32509
14	17	Jet-VOR	271	949	3228	3.4	3.5	11.9	1105	287758	32520
15	19	Jet-VOR	274	965	3380	3.5	3.5	12.3	1034	290744	32893
16	19	RNAV	275	916	2764	3.0	3.3	10.1	933	296658	33515
17	6	Jet-VOR	271	965	3015	3.1	3.6	11.1	1045	290359	32565
18	6	RNAV	273	907	2950	3.3	3.3	10.8	902	291455	32944
19	9	RNAV	270	919	3075	3.4	3.4	11.4	996	283746	32190
20	9	Jet-VOR	269	952	3150	3.3	3.5	11.7	1084	287057	32995

Note. Time is in seconds and distance is in nautical miles.

TABLE 15. FAST-TIME DATA MEASUREMENTS FROM ONE-SECTOR CONFIGURATION

Sample	Potential Conflicts	Time-In System (Seconds)	Distance Flown (nmi)	Aircraft Handled
R1	4	46,081	5,542.5	63
R6	8	49,695	5,908.5	63
R10	3	49,633	5,913.2	63
V1	10	60,297	7,248.0	69
V6	27	61,013	7,336.6	70
V10	18	60,616	7,319.8	69

TABLE 16. REAL-TIME DATA MEASUREMENTS FOR ONE-SECTOR CONFIGURATION

		Number of			Per Aircraft					
Run No.	Sample No.	Aircraft Handled	Push-to-Talk	Total Talk Time	Average Contact Duration	Average No. of Contacts	Average Talk Time	Control Messages	Time in System	Distance Flown
1	V10	69	174	635	3.6	2.5	9.2	333	61612	7416.2
2	V 6	69	192	681	3.5	2.8	9.9	297	61576	7357.4
3	V 1	69	230	779	3.4	3.3	11.3	275	60744	7268.2
4	V 1	68	212	711	3.4	3.1	10.5	347	60794	7348.3
5	V 6	69	219	696	3.2	3.2	10.1	277	62693	7434.9
6	V10	69	198	601	3.0	2.9	8.7	262	62003	7429.2
7	R 1	63	170	486	2.9	2.7	7.7	205	46281	5546.3
8	R 1	62	182	518	2.8	2.9	8.2	255	46921	5479.0
9	R10	62	144	455	3.2	2.3	7.2	194	51285	6081.4
10	R10	62	163	533	3.3	2.6	8.4	186	50136	5919.5
11	R 6	61	150	441	2.9	2.4	7.1	204	51499	6073.5
12	R 6	62	151	406	2.7	2.4	6.4	192	50030	5859.7
13	R 1	63	174	390	2.2	2.5	5.6	172	47504	5716.5
14	R 6	62	148	374	2.5	2.3	5.8	162	50167	6172.8
15	R 1	62	138	430	3.1	2.2	6.9	135	45301	5488.1
16	R10	62	146	356	2.4	2.2	5.4	157	49190	6026.9
17	V10	68	237	518	2.2	3.5	7.6	244	59876	7220.8
18	V 1	69	237	550	2.3	3.4	8.0	262	61733	7508.9
19	R10	62	157	492	3.1	2.5	7.8	135	49490	5904.1
20	R 6	62	195	574	2.9	3.0	8.9	161	49762	5913.9
21	V 6	69	211	479	2.3	2.9	6.7	225	59870	7237.5
22	V 1	68	220	601	2.7	3.2	8.7	240	60476	7242.6
23	V10	69	221	626	2.8	3.2	9.1	213	61321	7341.3
24	V 6	69	203	575	2.8	2.9	8.3	207	61473	7347.4

Note. Time is in seconds and distance in nautical miles.

obtain objective data which would allow the effect of potential conflicts on controller workload and system user activity to be identified or measured. Therefore, statistical analyses of potential conflicts were limited to the one-sector tests.

<u>FIRST EXPECTED RESULTS</u>. The F ratio of the analysis of variance statistical tests was used for messages of the two ATC systems. The means of the samples were tested for differences between the RNAV and Jet-VOR route configurations, and the breakdown of the individual communication messages is presented in table 17. For all the controller-to-pilot communication measures except average radio contact duration, the RNAV route configuration was significantly superior. There was no significant difference between the system configurations for time in system, distance flown, and flights handled. The sample means are listed in table 18.

The reduction in controller workload measures (communications contact, total communications time, and number of control instructions issued) found for RNAV compared to VOR-radar vector control was similar to but not as pronounced as that found in previous terminal area simulations (references 6 and 7).

<u>SECOND EXPECTED RESULTS</u>. The second expected result of the experiment was the correlation of fast-time and real-time simulation results for the single-sector configuration. The correlation coefficient is a statistical measure of the linear relationship between two variables. By definition the coefficient must be between -1 and +1. A coefficient close to +1 (-1) means a positive (negative) relationship; that is, as one variable increases, the other also increases (decreases).

Because of the lack of balance between the RNAV and Jet-VOR single-sector route structures in the one-sector tests, it was not statistically valid to estimate the correlations between the RNAV and Jet-VOR data. The matrix of correlation coefficients for the RNAV-alone data is presented in table 19. Since there was no variation in the fast-time number of flights handled for RNAV, its correlation with other measures could not be estimated. The fast-time distance flown and time in system are highly correlated with the corresponding real-time measures. Figures 10, 11, and 12 are scatter plots illustrating this correlation for the one-sector tests. The sample correlations between the real-time number of flights handled, the fast-time distance flown, and time-in-system measures were significant and negative. After examining the data, it appears that this was a spurious result due to the small, integer variation in the number of flights handled. Communication measures were not correlated with the fast-time measures.

The matrix of correlation coefficients is presented in table 20 for the Jet-VOR data. The lack of correlation between the fast-time and real-time distance flown and time-in-system measures has two possible causes. The variation in these measures was small, and several real-time measurements were substantially higher or lower than the other measurements. Figures 13, 14, and 15 are scatter plots of time in system and distance flown for the one-sector tests.

TABLE 17. AVERAGE COMMUNICATION MESSAGE BREAKDOWNS FOR FIVE SECTOR CONFIGURATION

	Offset	Cancel Offset	Direct to Waypoint	Direct to NAVAID	Resume Flt.Plan	Vector Changes	Altitude Changes	Speed Changes	Total of Control Clearances	Misc. Messages	Total
Jet-VOR	0.0	0.0	0.0	50.1	172.5	114.0	257.3	25.3	619.2	457.2	1,076.4
RNAV	21.1	21.2	18.2	0.0	169.9	24.4	255.5	14.9	525.2	416.9	942.1

TABLE 18. ATC SYSTEM DATA MEASURE AVERAGES BASED ON FIVE-SECTOR CONFIGURATION

	Route Configuration		
Data Measure	Jet-VOR	RNAV	Significance = .05
Total Push-to-Talk	999.8	923.6	Yes
Average Contact Duration	3.21	3.22	No
Average Number Contacts	3.67	3.40	Yes
Average Talk Time per Aircraft	11.82	10.96	Yes
Number Control Messages	1,076.4	942.1	Yes
Time in System	291,653.6	288,266.3	No
Distance Flown	33,013.7	32,618.5	No
Flights Handled	271.7	272.0	No

Note. Time is measured in seconds and distance in nautical miles. Average is on a per aircraft basis for the measure.

TABLE 19. CORRELATION OF FAST- AND REAL-TIME MEASURES, RNAV CORRELATION MATRIX

		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Fast-Time Measures	(1) Time in System	1.00	.99	-	-.60	-.26	-.02	.18	-.21	.01	-.26	.91	.90
	(2) Distance Flown		1.00	-	-.60	-.27	-.01	.19	-.22	.01	-.26	.91	.90
	(3) Flights Handled			-	-	-	-	-	-	-	-	-	-
Real-Time Measures	(4) Flights Handled				1.00	.35	-.05	-.33	.20	-.14	-.03	-.59	-.48
	(5) Push-to-Talk					1.00	.67	-.11	.95	.56	.35	-.19	-.33
	(6) Total Talk Time						1.00	.66	.82	.99	.26	-.02	-.27
	(7) Average Duration of Radio Contact							1.00	.14	.74	.02	.13	-.06
	(8) Average Number of Contacts								1.00	.76	.45	-.15	-.36
	(9) Average Talk-Time per Aircraft									1.00	.27	-.00	-.26
	(10) Control Messages										1.00	.01	-.25
	(11) Time in System											1.00	.91
	(12) Distance Flown												1.00

TABLE 20. CORRELATION OF FAST- AND REAL-TIME MEASURES, JET-VOR CORRELATION MATRIX

		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Fast-Time Measures	(1) Time in System	1.00	.92	.90	.47	-.40	-.25	.00	-.44	-.27	-.28	.23	.01
	(2) Distance Flown		1.00	.65	.44	-.47	-.32	-.02	-.47	-.34	-.28	.23	.03
	(3) Flights Handled			1.00	.41	-.26	-.11	.02	-.32	-.15	-.23	.19	-.01
Real-Time Measures	(4) Flights Handled				1.00	-.33	.08	.20	-.41	.03	-.16	.57	.50
	(5) Push-to-Talk					1.00	-.11	-.61	.98	-.09	-.40	-.33	-.25
	(6) Total Talk Time						1.00	.85	-.04	.99	.57	.38	.16
	(7) Average Duration of Radio Contact							1.00	-.54	.84	.72	.46	.26
	(8) Average Number of Contacts								1.00	-.01	-.32	-.26	-.21
	(9) Average Talk Time per Aircraft									1.00	.59	.38	.16
	(10) Control Messages										1.00	.23	.33
	(11) Time in System											1.00	.87
	(12) Distance Flown												1.00

THIRD EXPECTED RESULTS. This section examines the relationship of controller workload and system impact to predetermined quantities of potential aircraft conflict situations. Regression equations were fit to the real-time measures for each configuration, with potential conflicts (as determined in fast-time simulations of the same traffic samples, route structures, and geographic areas) as the independent variable.

The regression coefficient would be nonzero if any relationship existed between the measure and the number of potential conflicts. In every case, the regression coefficient was not significantly different from zero. Scatter plots showing the performance measures plotted versus potential conflicts are included in figures 16 through 24. As can be seen, the results with respect to the number of potential conflicts did not demonstrate any consistent trends.

INCREASED POTENTIAL CONFLICT SEPARATION CRITERIA EFFECT. It was hypothesized that the correlation between potential conflicts and the real-time measures was obscurred by the use of standard conflict separation criteria. In order to investigate this possibility, two additional horizontal separation criteria of 7 and 10 nmi were tested. The computer programs were rerun for the single-sector fast-time samples to obtain the number of potential conflicts under these criteria. The results are shown in table 21.

TABLE 21. NUMBER OF POTENTIAL CONFLICTS FROM INCREASED HORIZONTAL SEPARATION CRITERIA

Sample		5 nmi	7 nmi	10 nmi
Jet-VOR	1	10	16	24
	6	27	34	39
	10	18	27	30
RNAV	1	4	11	13
	6	8	11	11
	10	3	4	9

In the RNAV samples, the first and sixth samples changed places in order of magnitude when the separation criterion was increased from 5 to 10 nmi. The relative changes in the number of potential conflicts were not substantial for the Jet-VOR data. Figures 25 through 32 illustrate the relationships between the potential conflicts and the following data measures: time in system, number of aircraft handled, total talk time, and average contact duration. The differences in the average responses between the RNAV and Jet-VOR results, as shown in the scatter plots, are due to differences in the traffic densities of the RNAV and Jet-VOR samples. Because of these inherent traffic differences, the RNAV and Jet-VOR results were analyzed separately. As can be seen, the real-time measurements appear independent of the number of potential conflicts for either separation criterion. No correlation was observed between potential conflicts and the representative real-time data measures for the potential conflict separation criteria of 7 and 10 nmi.

CONCLUSIONS

Based on the statistical results presented, it is concluded that:

FAST TIME.

1. The Lincoln Laboratory fast-time data for the number of potential conflicts and the average traffic load (aircraft density per sample) for the 2-hour data period compared to the fast-time simulation test samples herein show no real difference for the aggregate of these measures.

2. The number of potential conflicts generated in the fast-time tests was significantly greater in the Jet-VOR system than in the RNAV system in tests of both the one- and five-sector configurations.

REAL TIME.

1. There is a significant reduction in controller's workload (total communications time, number of contracts, and number of control instructions issued) using the RNAV system versus using the Jet-VOR system. In this respect, the results of this enroute simulation are similar to, but not as marked as those found in previous terminal area simulations which compared RNAV to non-RNAV terminal area environments.

2. Based on the five-sector data, the statistical tests do not substantiate a real difference between the Jet-VOR and RNAV systems for real-time time-in-system and distance-flown measures.

3. Controller performance and system user measures in real-time simulation do not demonstrate any consistent trends of correlation with the number of potential conflicts found in the fast-time simulations.

4. The number of potential conflicts measured for a particular route structure is very dependent upon the timing and altitude profiles of aircraft in the traffic sample. In real life, any control action which affects the altitude profile or effective speed of an aircraft significantly disrupts the potential conflict situation from that point forward. The sensitivity of the potential conflict measure to control changes of this sort reduces the possibility of establishing any relationship between the fast-time potential conflict measure and real-time system and system user measures. Therefore, little useful correlation between these measures was found.

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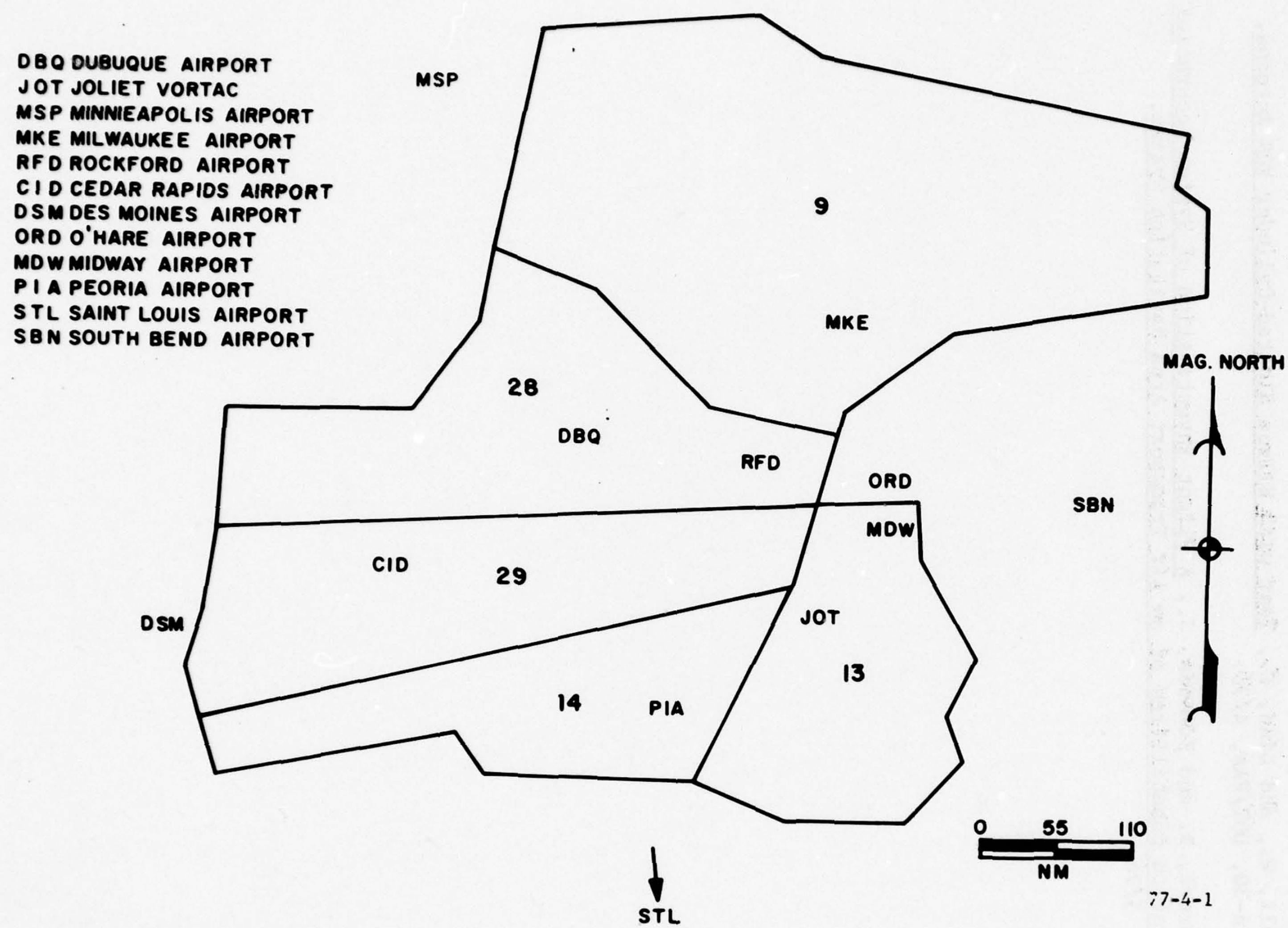

FIGURE 1. SIMULATED AREA OF CHICAGO ARTCC

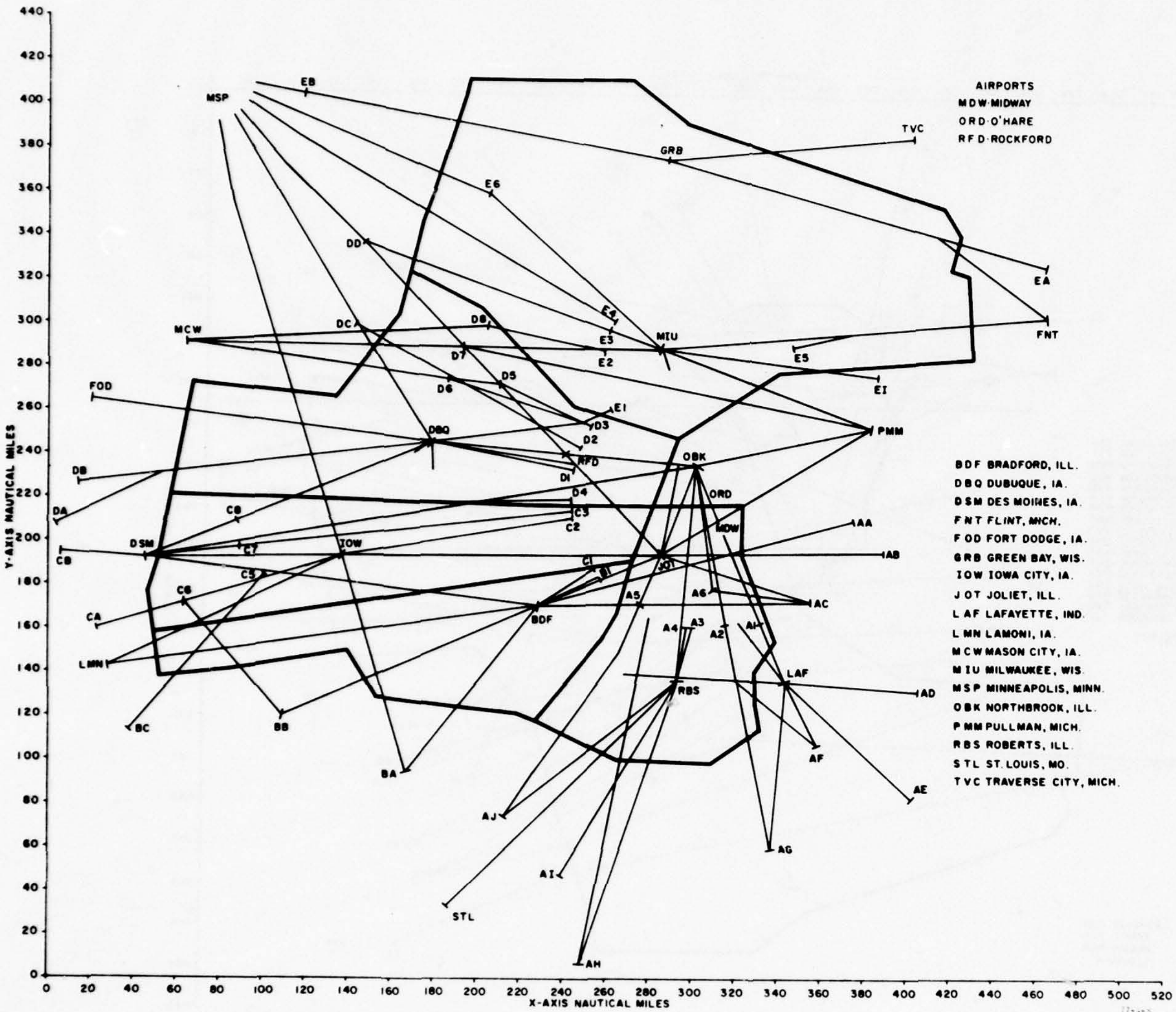

FIGURE 2. COMPOSITE JET-VOR ROUTES--FIVE SECTORS

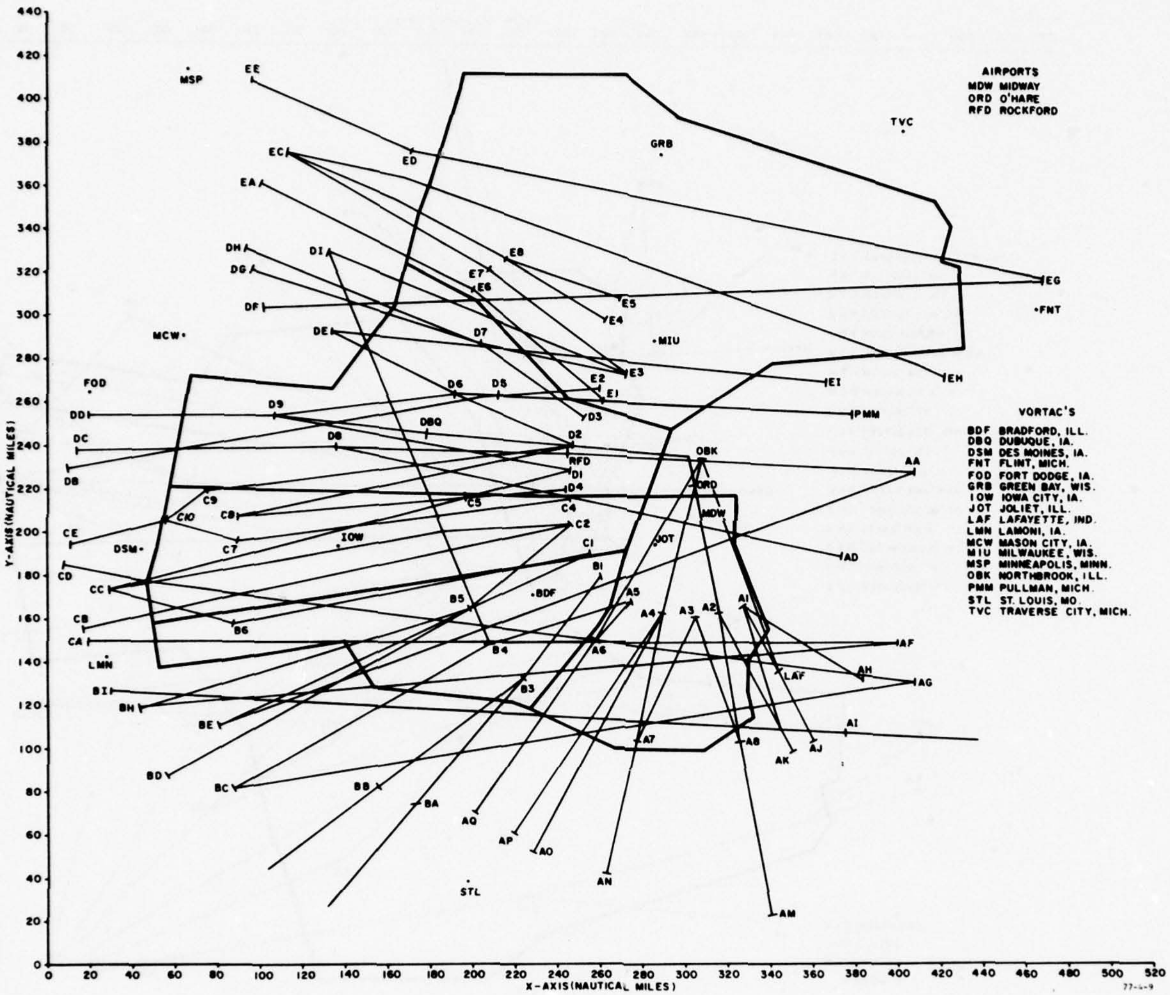

FIGURE 3. COMPOSITE RNAV ROUTES--FIVE SECTORS

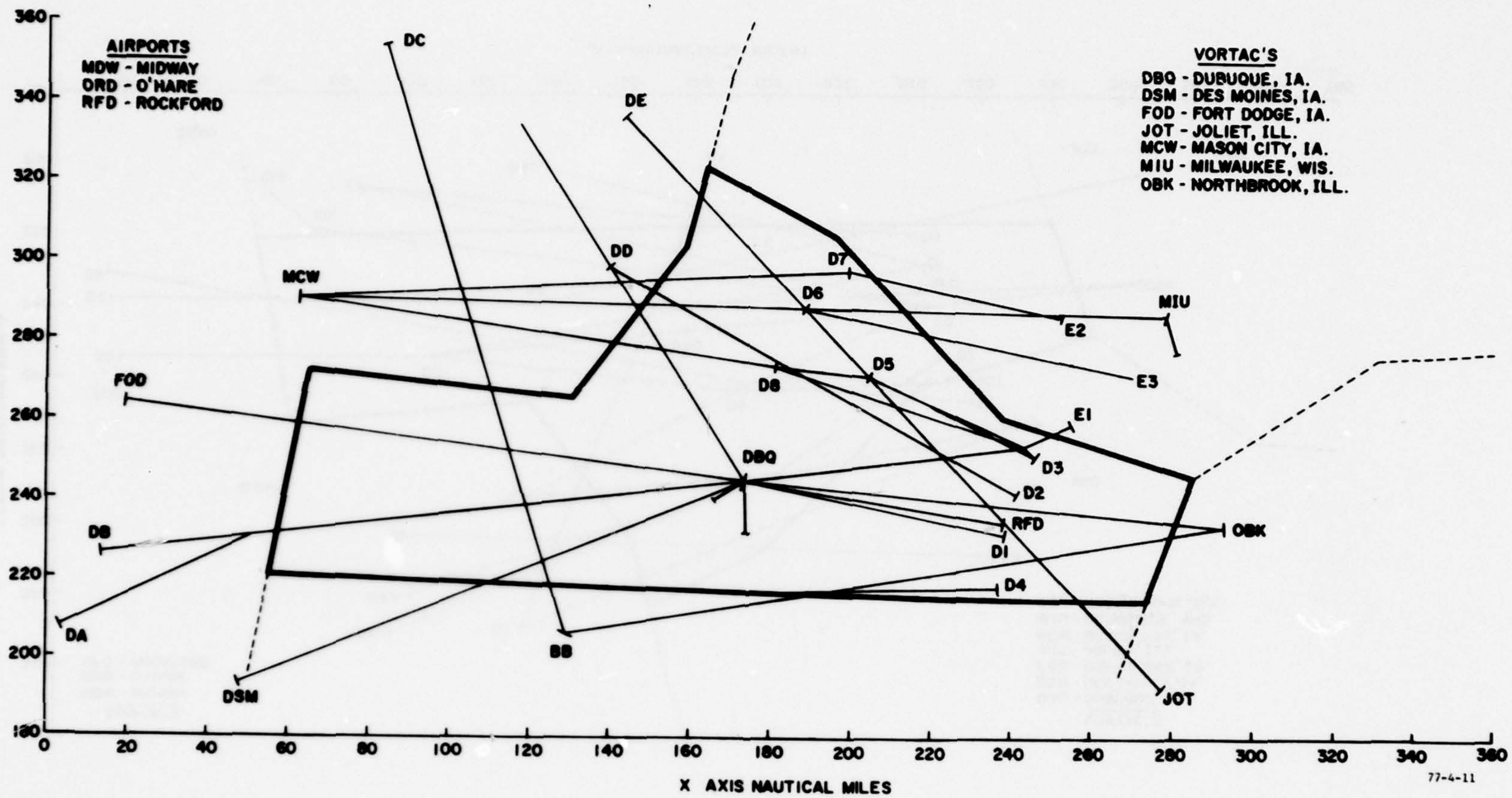

FIGURE 4. COMPOSITE JET-VOR ROUTES--ONE SECTOR

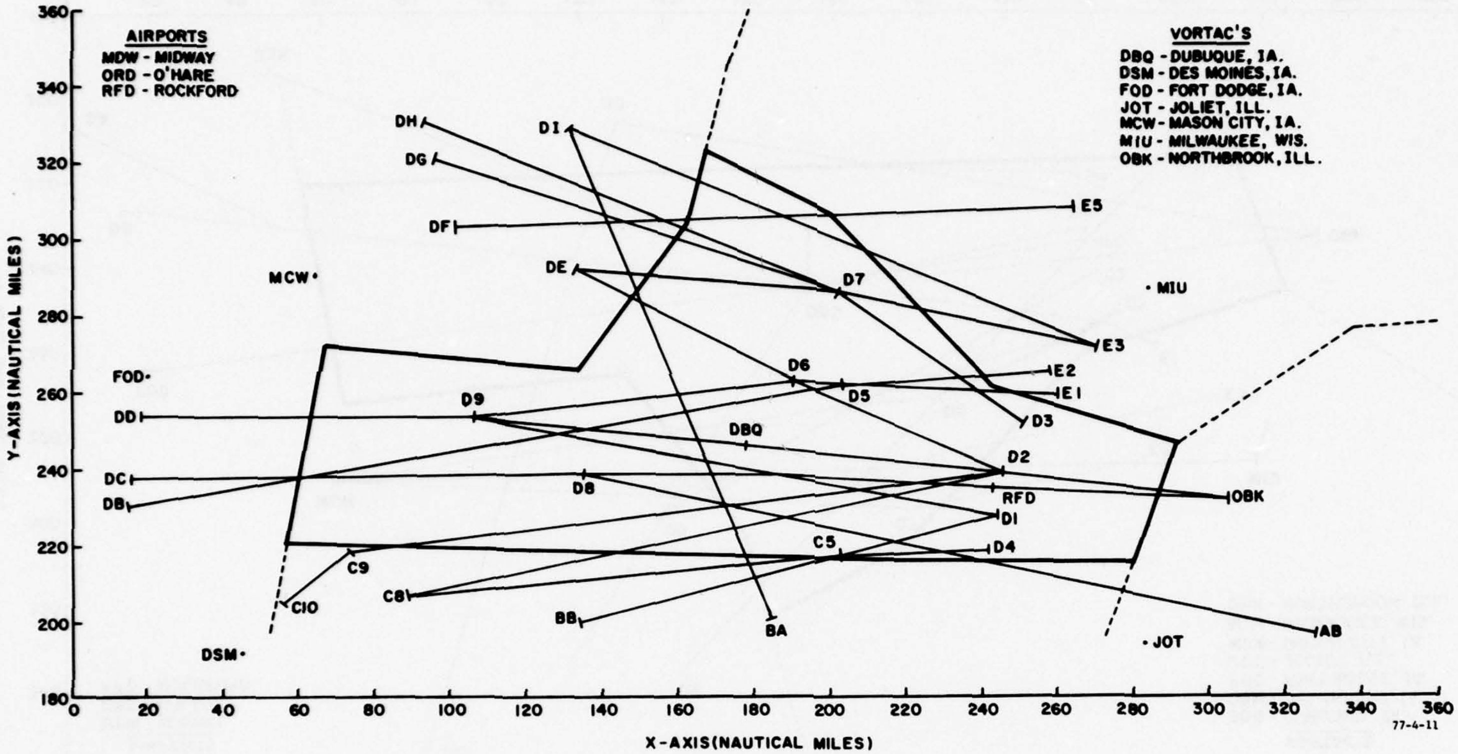

FIGURE 5. COMPOSITE RNAV ROUTES--ONE SECTOR

FIGURE 6. DIGITAL SIMULATION FACILITY (DSF) COMPUTER SYSTEM

FIGURE 7. DSF PILOT POSITIONS AND KEYBOARDS

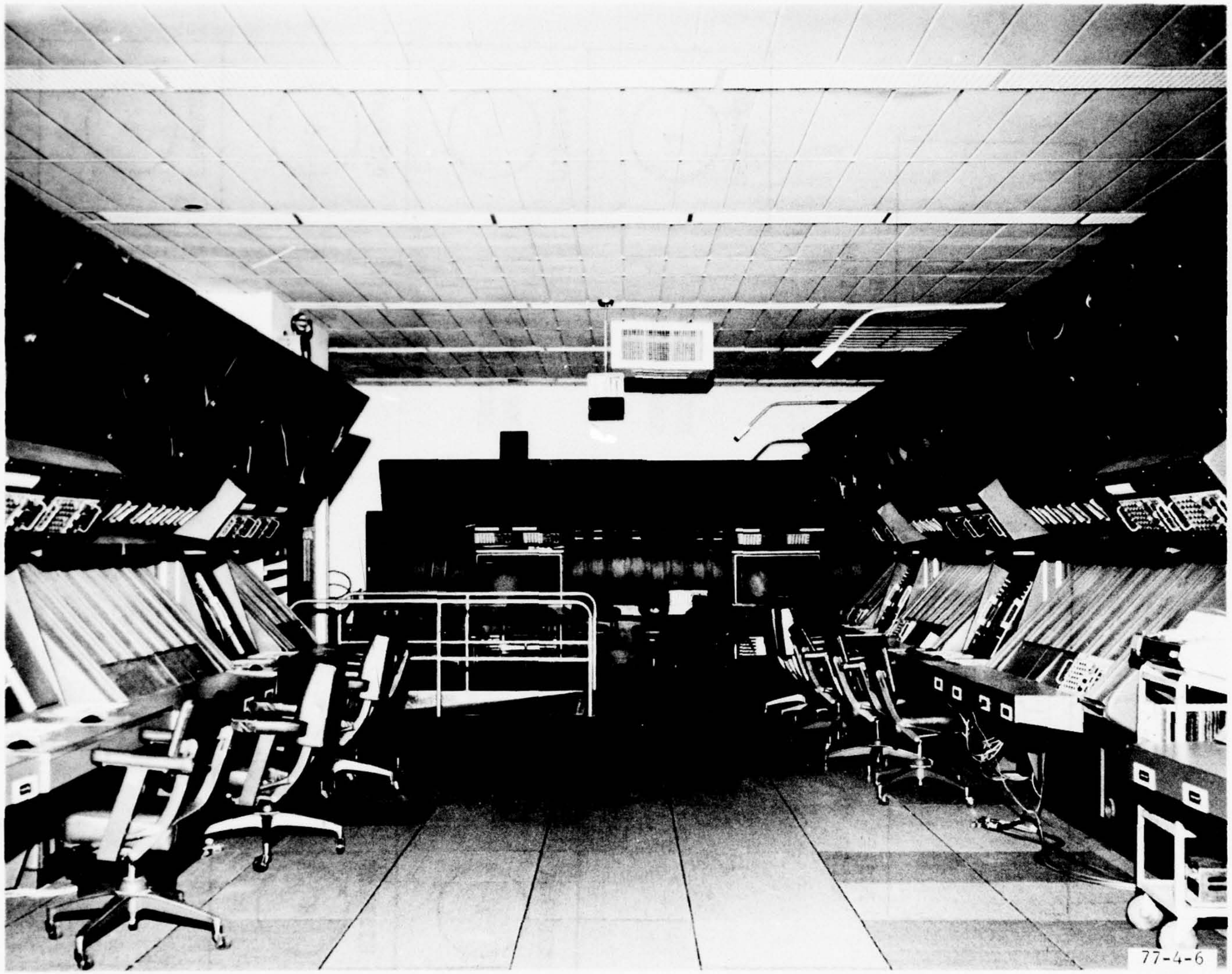

FIGURE 8. AIR TRAFFIC CONTROL (ATC) LABORATORY

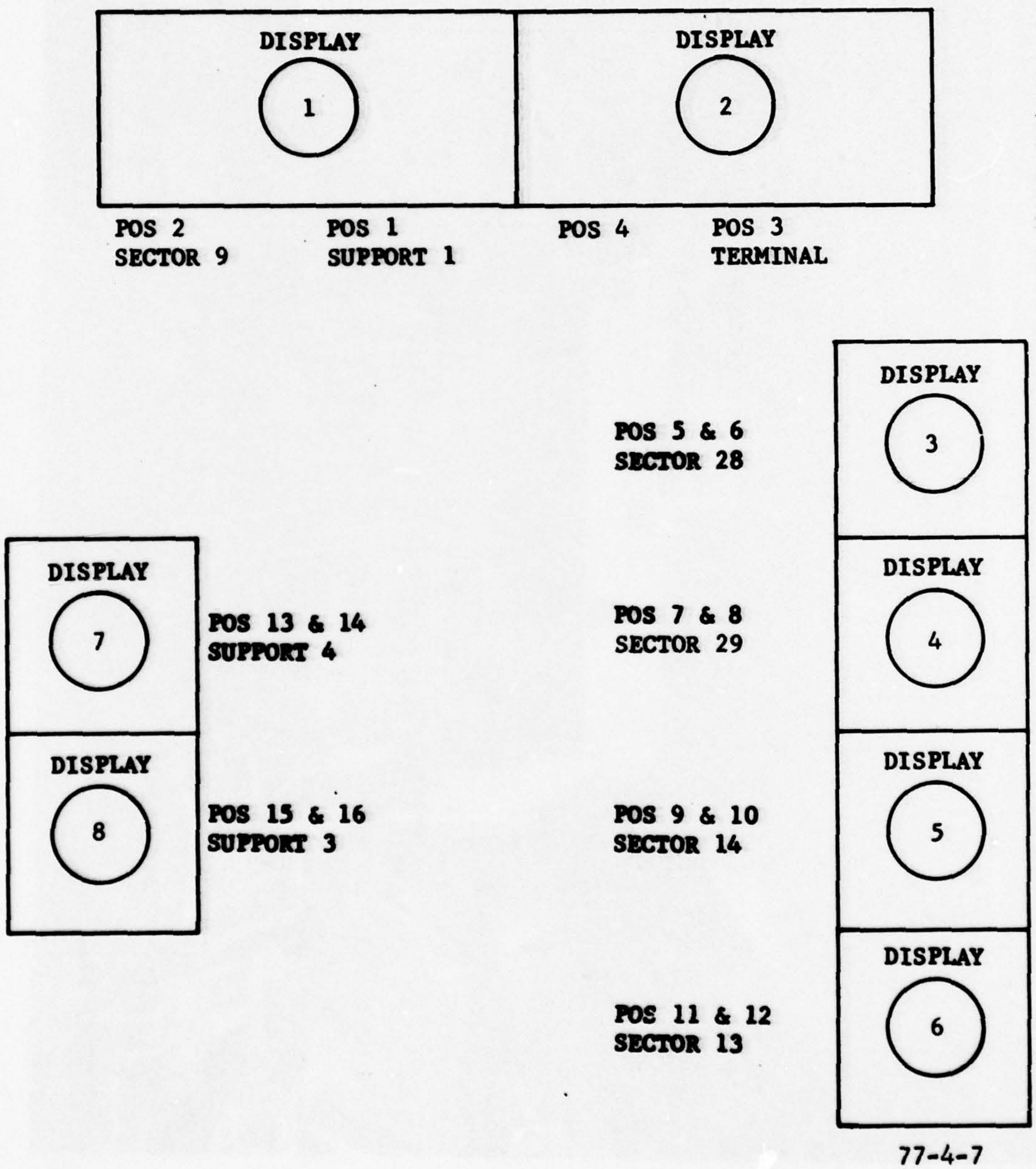

FIGURE 9. LABORATORY CONFIGURATION

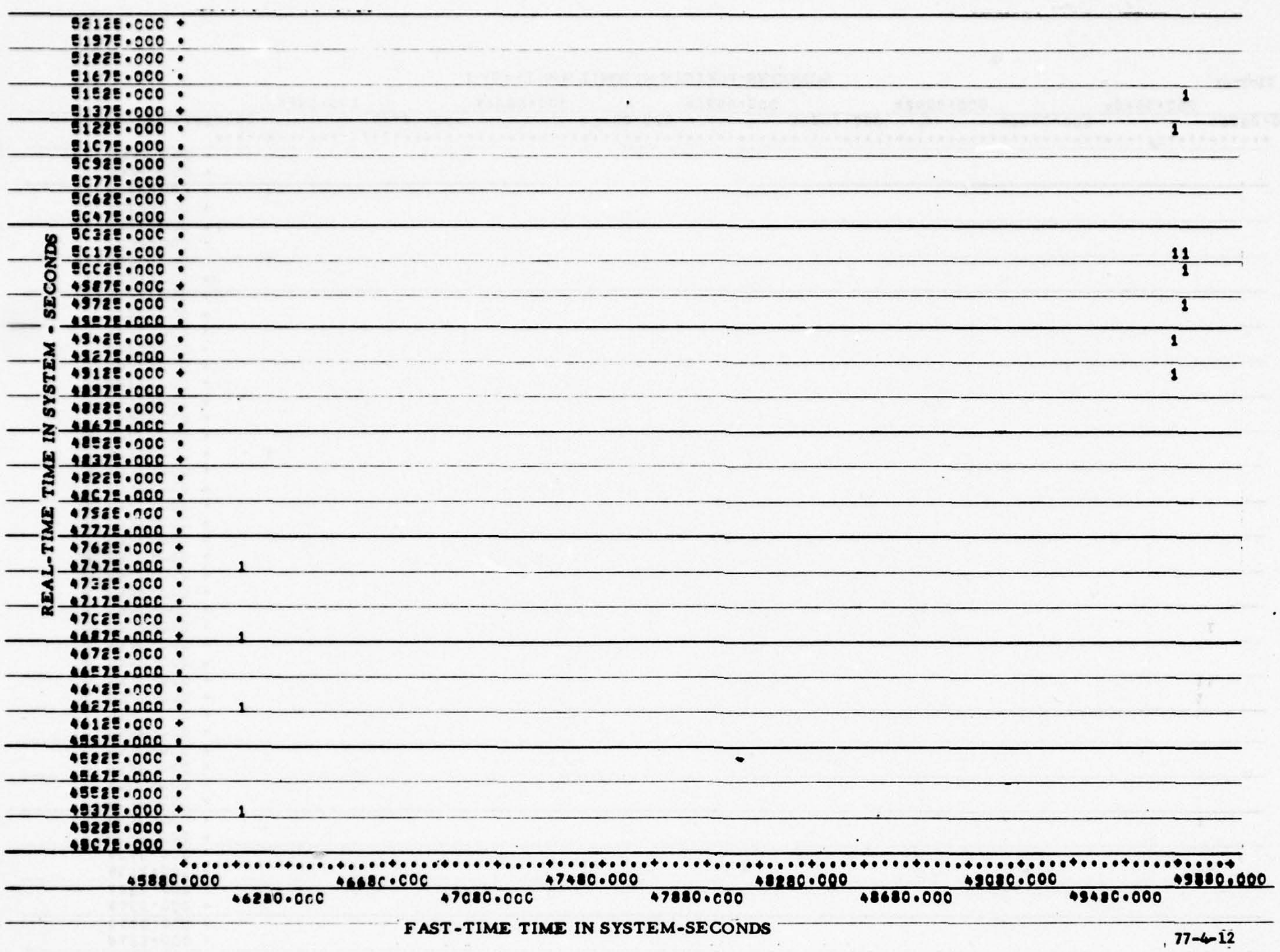

FIGURE 10. FAST-TIME TIME-IN-SYSTEM VERSUS REAL-TIME TIME-IN-SYSTEM PER RUN, RNAV—ONE SECTOR

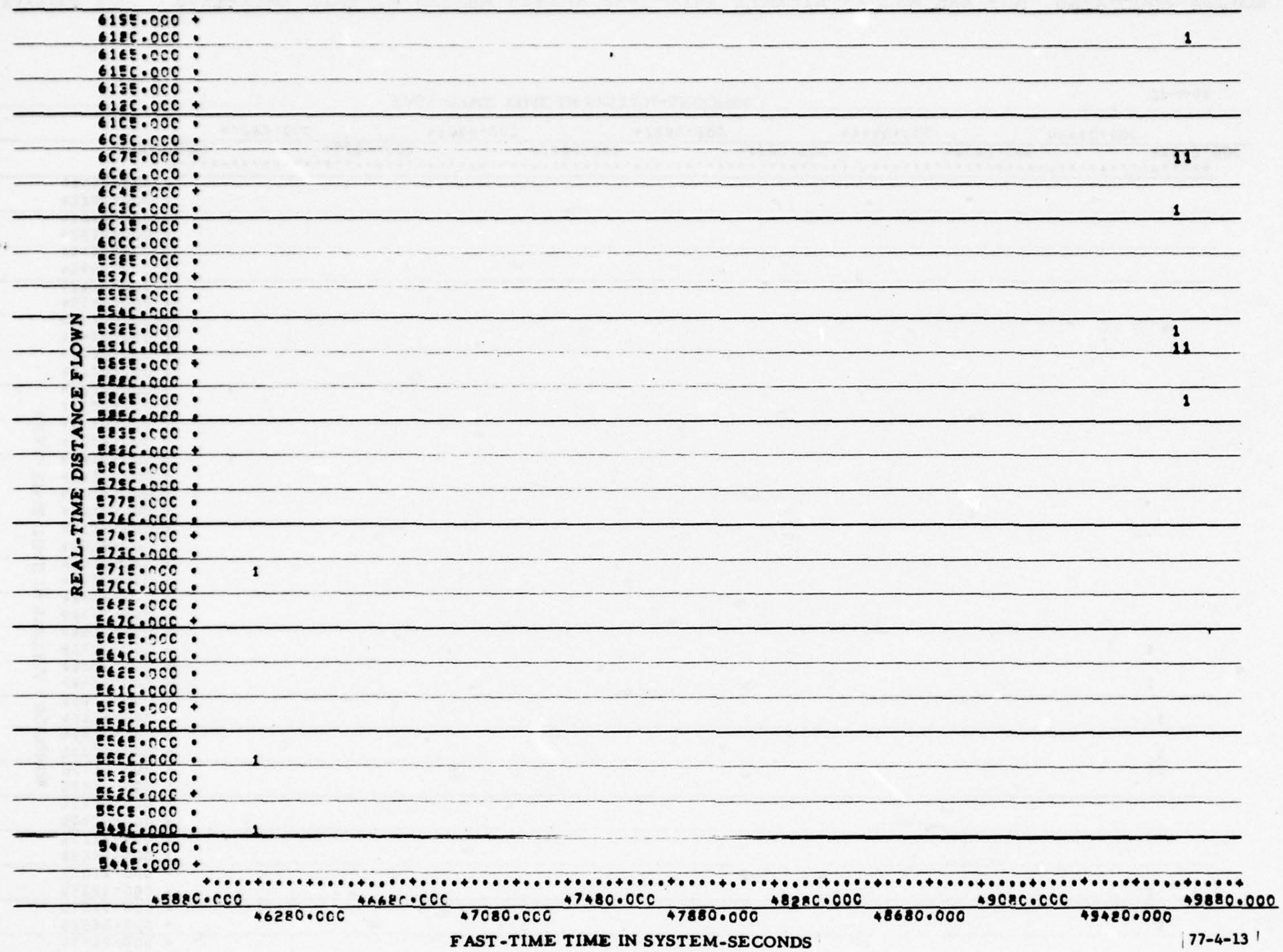

FIGURE 11. FAST-TIME TIME-IN-SYSTEM VERSUS REAL-TIME DISTANCE FLOWN , PER RUN, RNAV--ONE SECTOR

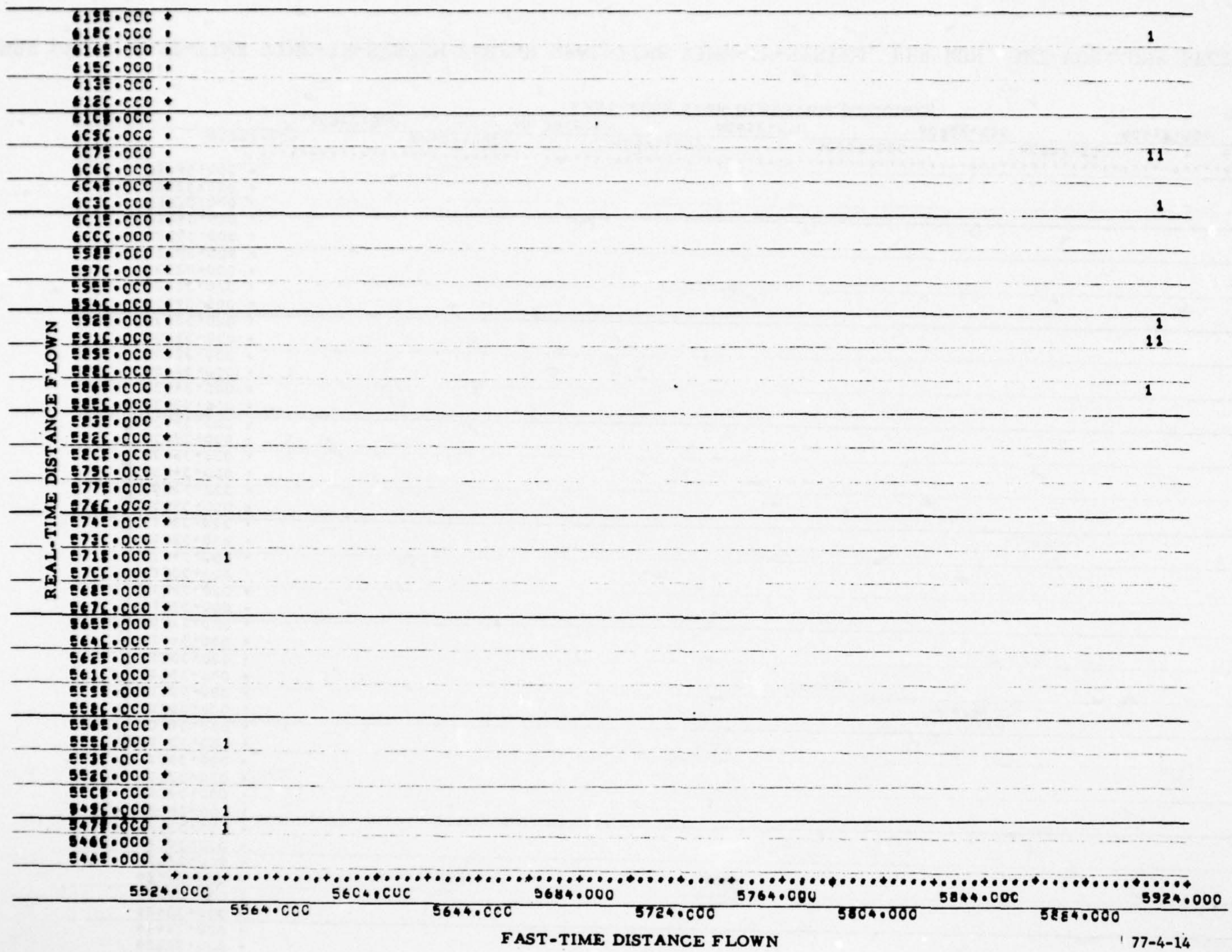

FIGURE 12. FAST-TIME DISTANCE FLOWN VERSUS REAL-TIME DISTANCE FLOWN, PER RUN, RNAV--ONE SECTOR

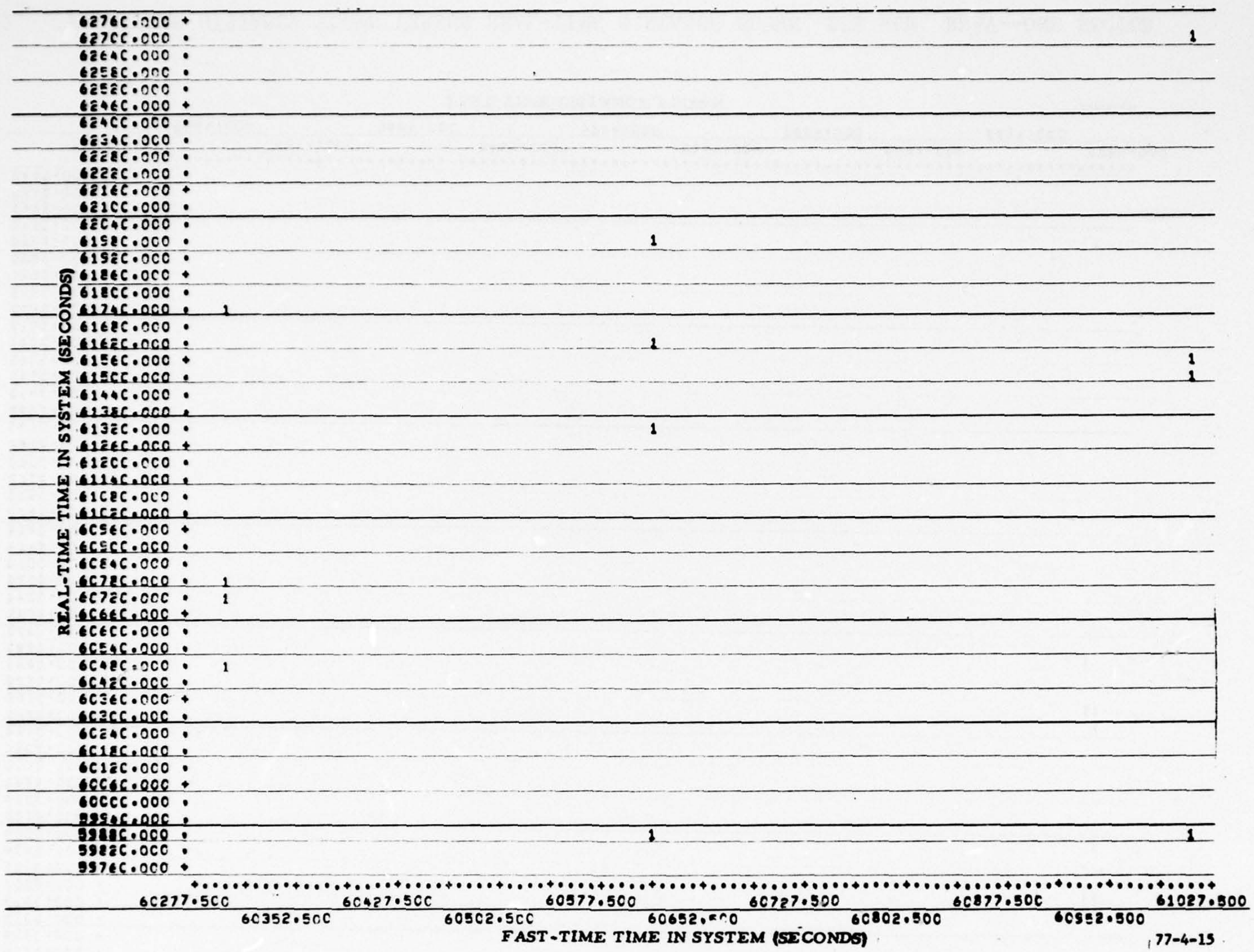

FIGURE 13. FAST-TIME TIME-IN-SYSTEM VERSUS REAL-TIME TIME-IN-SYSTEM, PER RUN, JET-VOR--ONE SECTOR

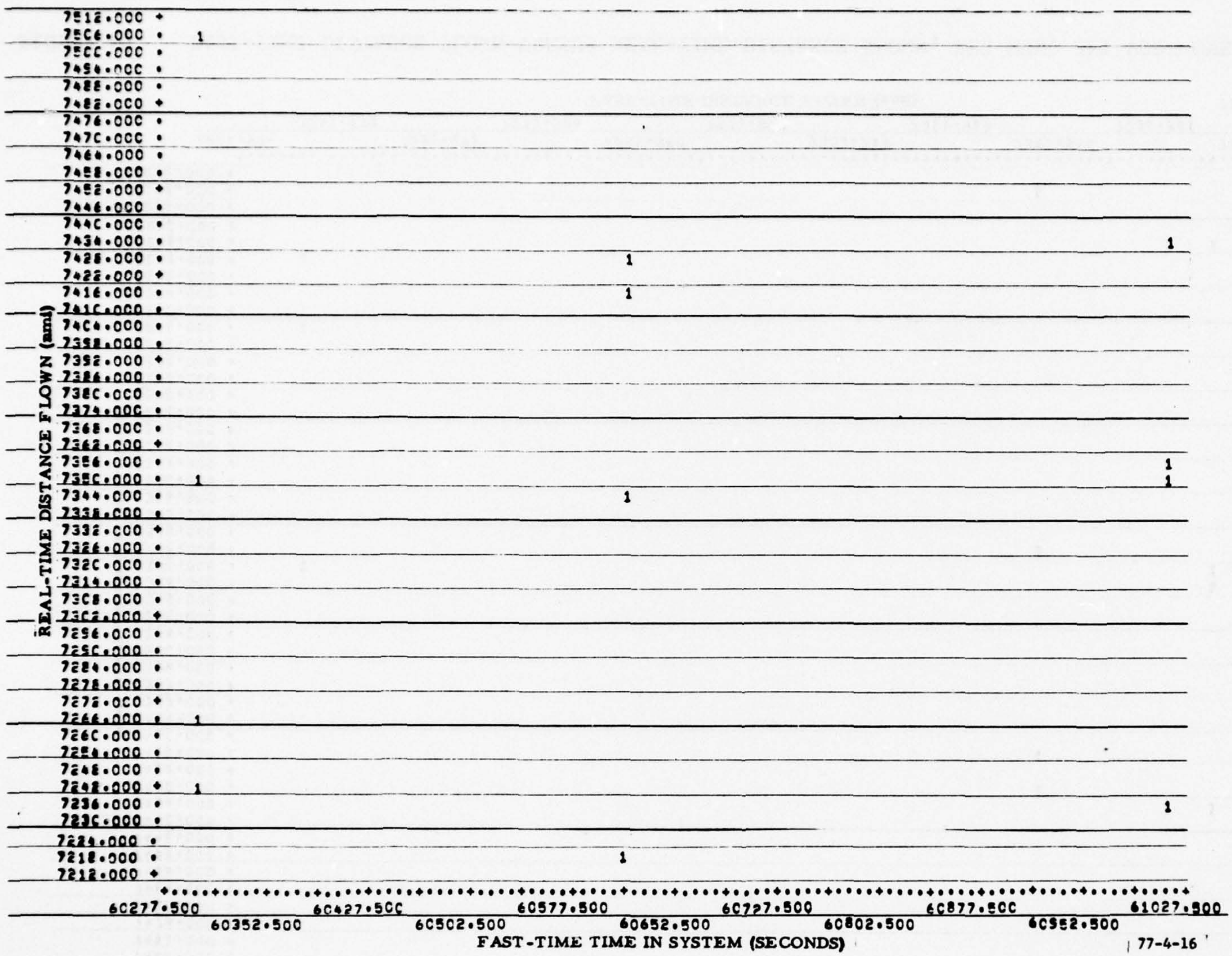

FIGURE 14. FAST-TIME TIME-IN-SYSTEM VERSUS REAL-TIME DISTANCE FLOWN, PER RUN, JET-VOR--ONE SECTOR

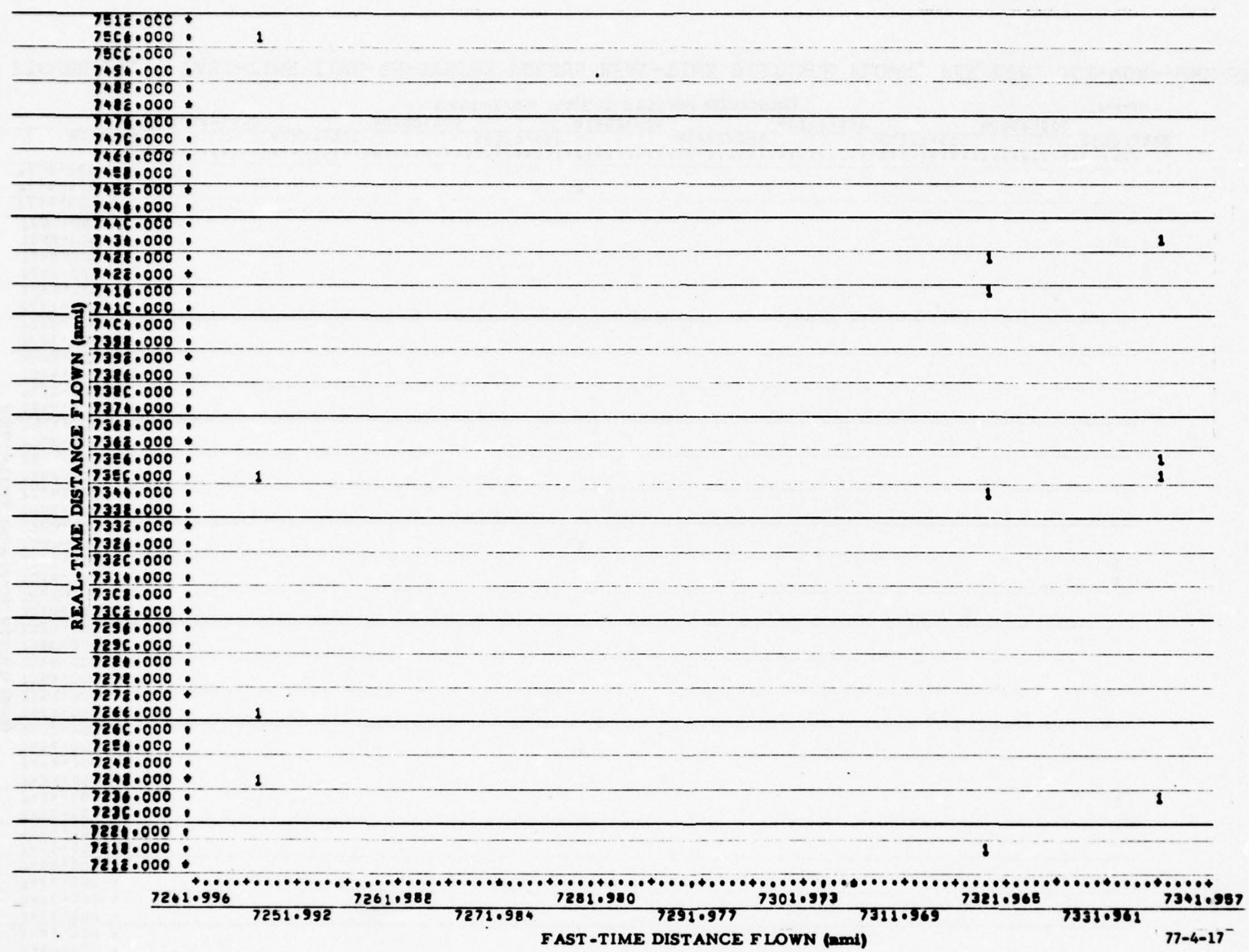

FIGURE 15. FAST-TIME DISTANCE FLOWN VERSUS REAL-TIME DISTANCE FLOWN, PER RUN, JET-VOR--ONE SECTOR

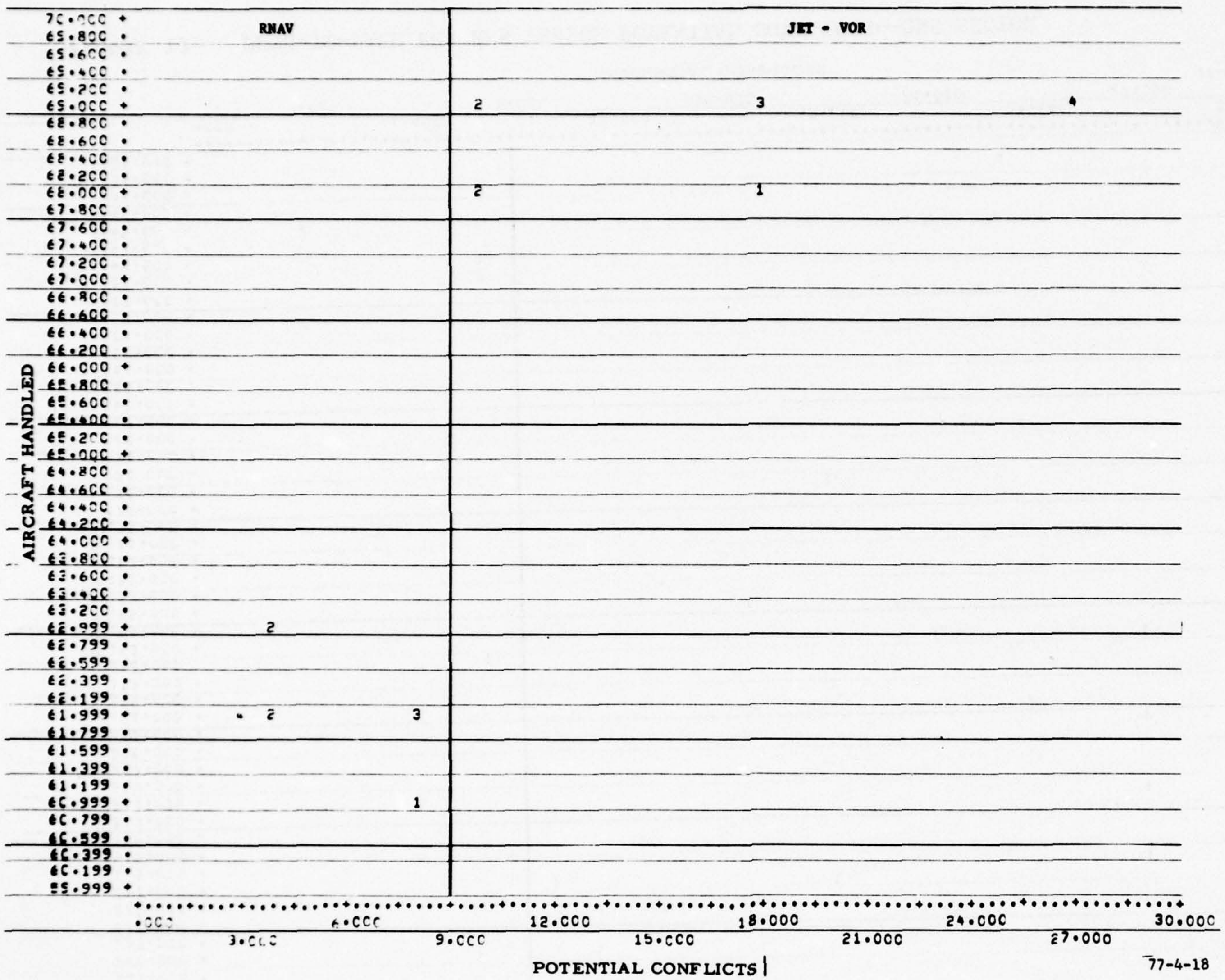

FIGURE 16. AIRCRAFT HANDLED PER RUN VERSUS POTENTIAL CONFLICTS--ONE SECTOR

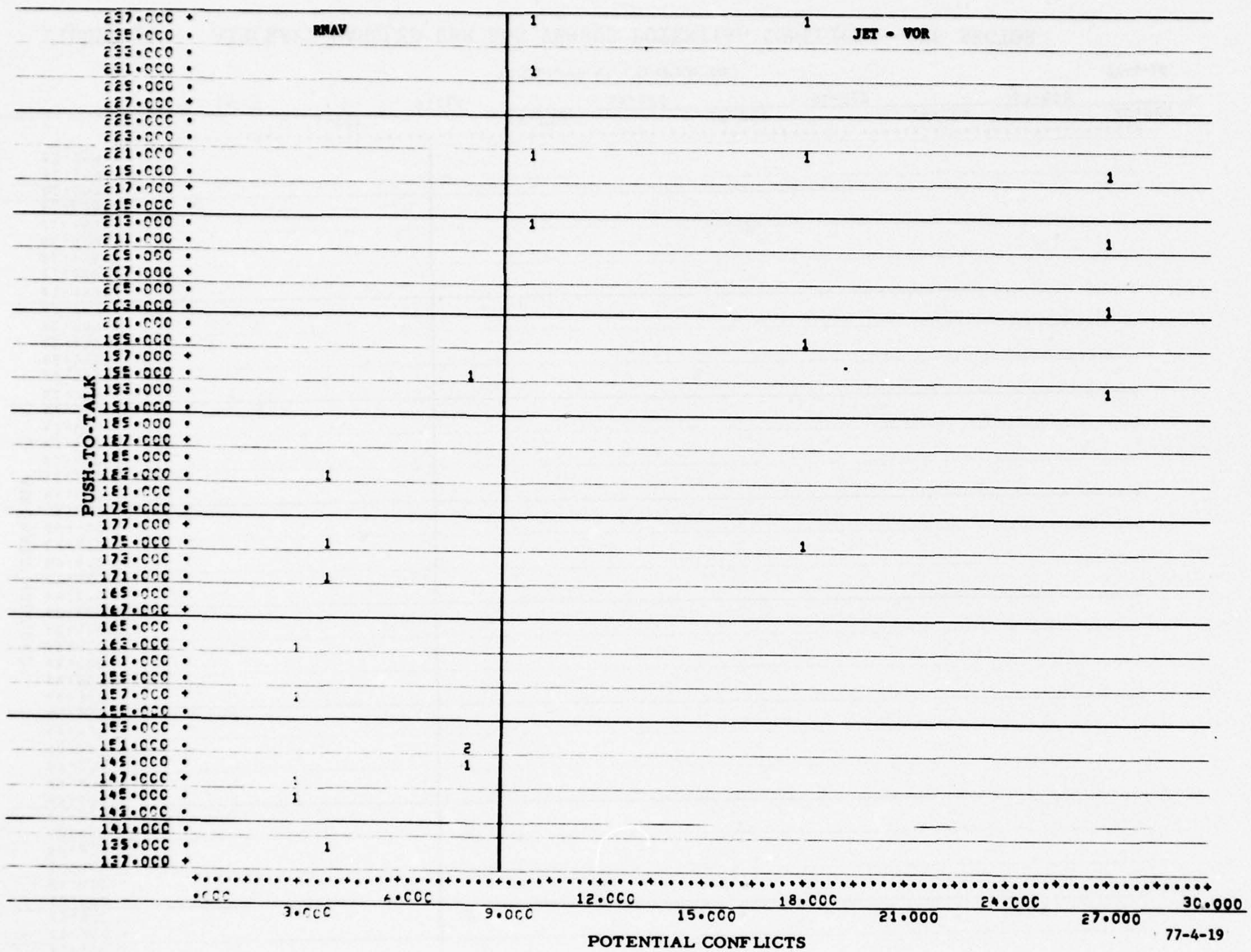

FIGURE 17. PUSH-TO-TALK PER RUN VERSUS POTENTIAL CONFLICTS--ONE SECTOR

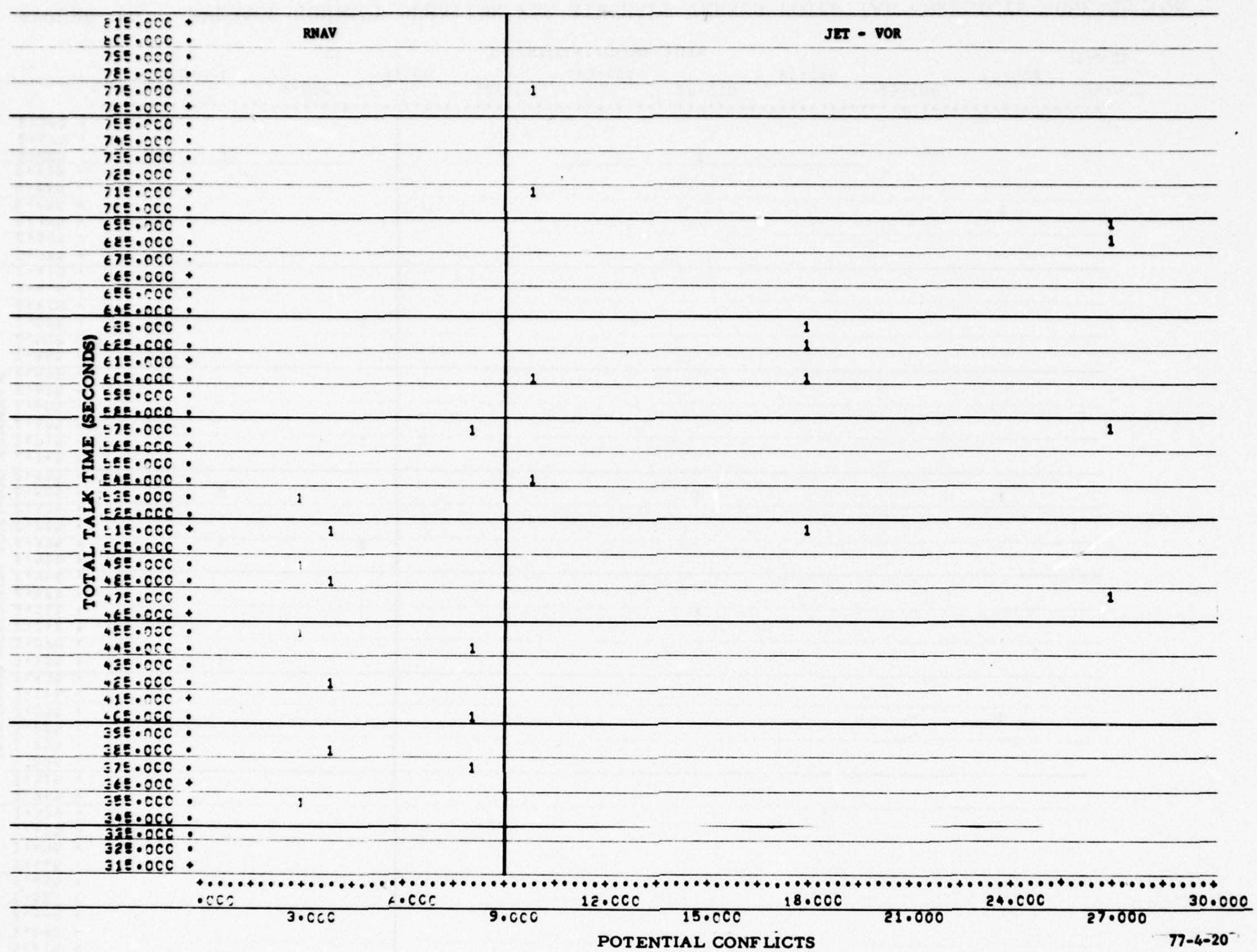

FIGURE 18. TOTAL TALK TIME PER RUN VERSUS POTENTIAL CONFLICTS--ONE SECTOR

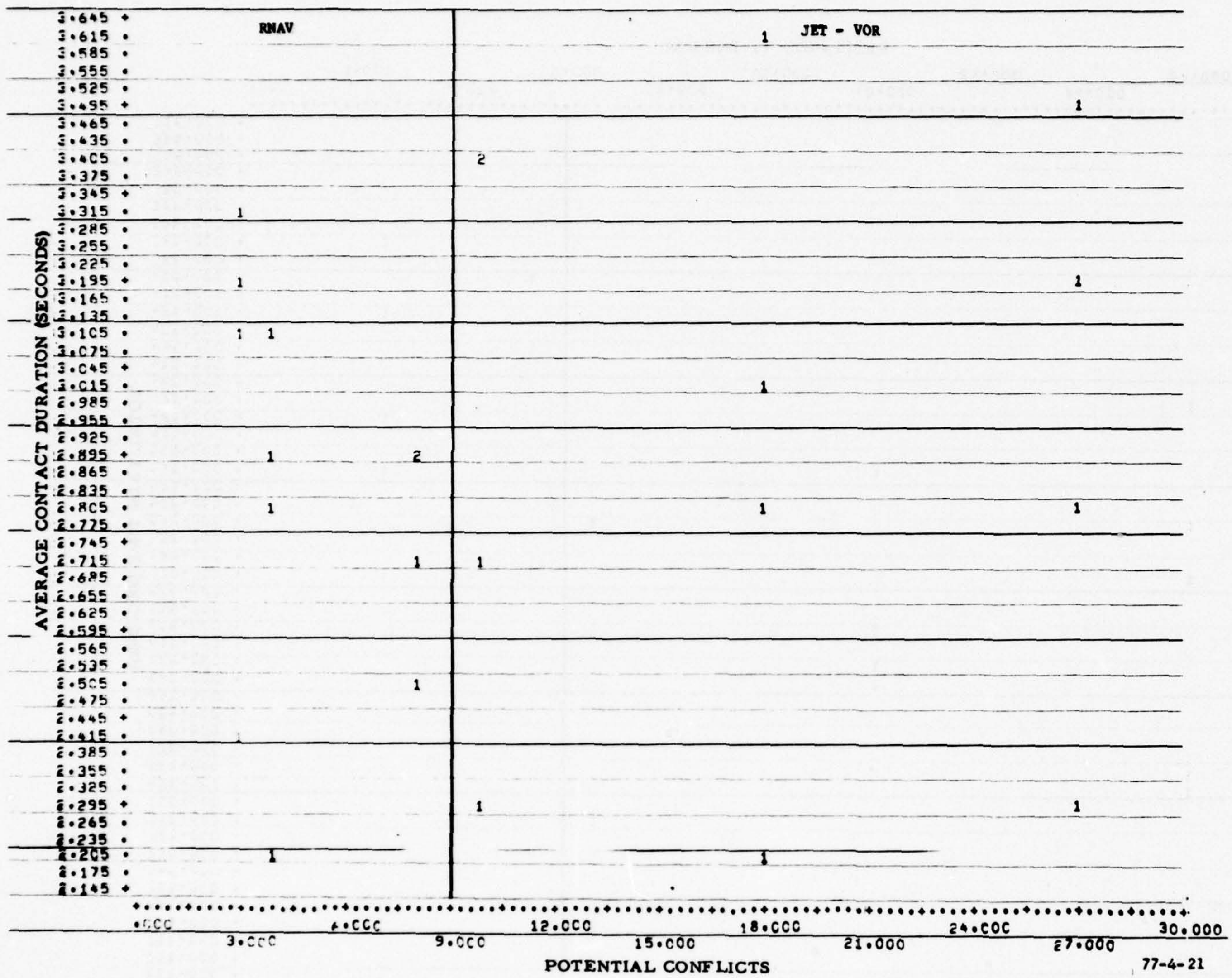

FIGURE 19. AVERAGE CONTACT DURATION PER AIRCRAFT VERSUS POTENTIAL CONFLICTS--ONE SECTOR

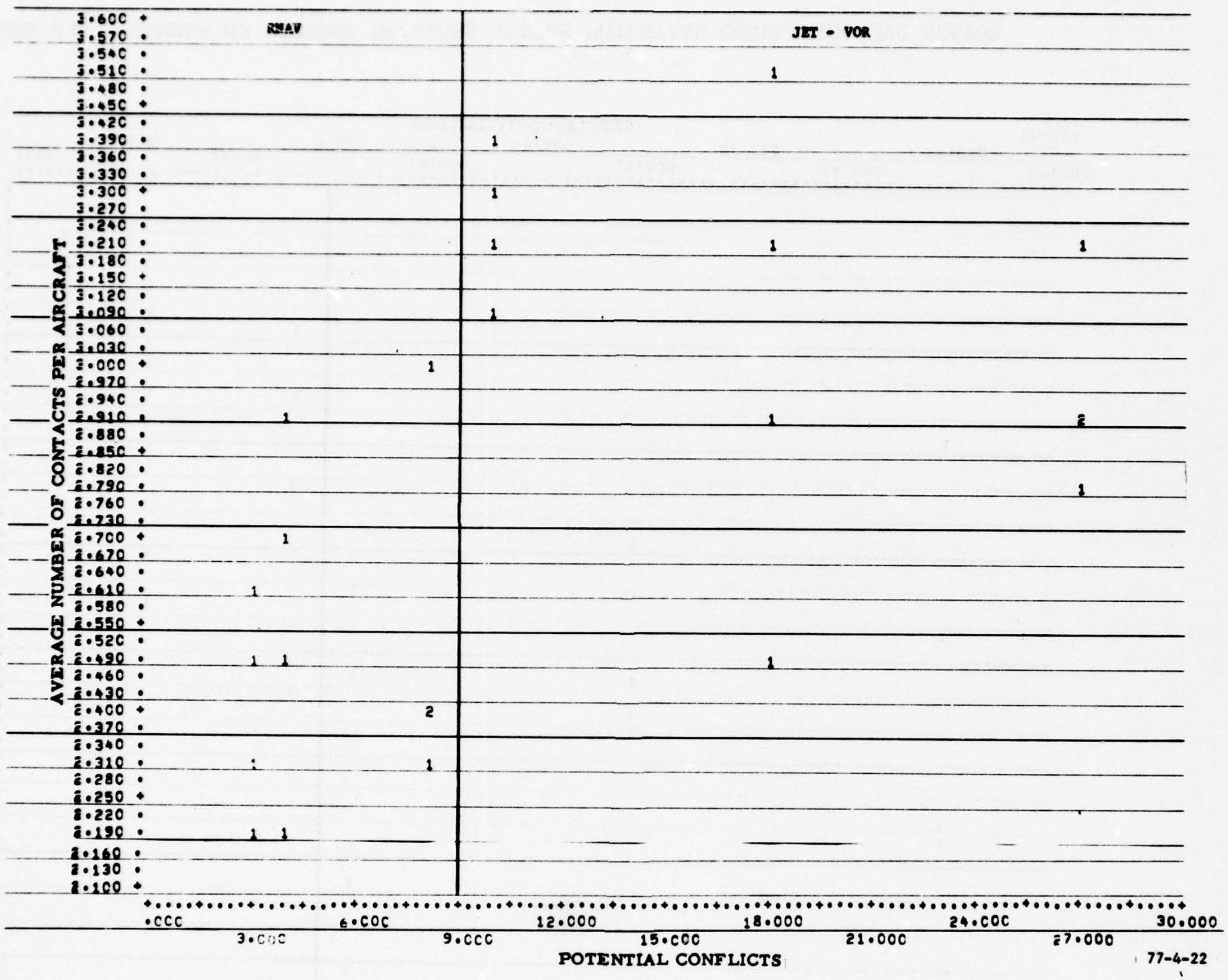

FIGURE 20. AVERAGE NUMBER OF CONTACTS PER AIRCRAFT VERSUS POTENTIAL CONFLICTS--ONE SECTOR

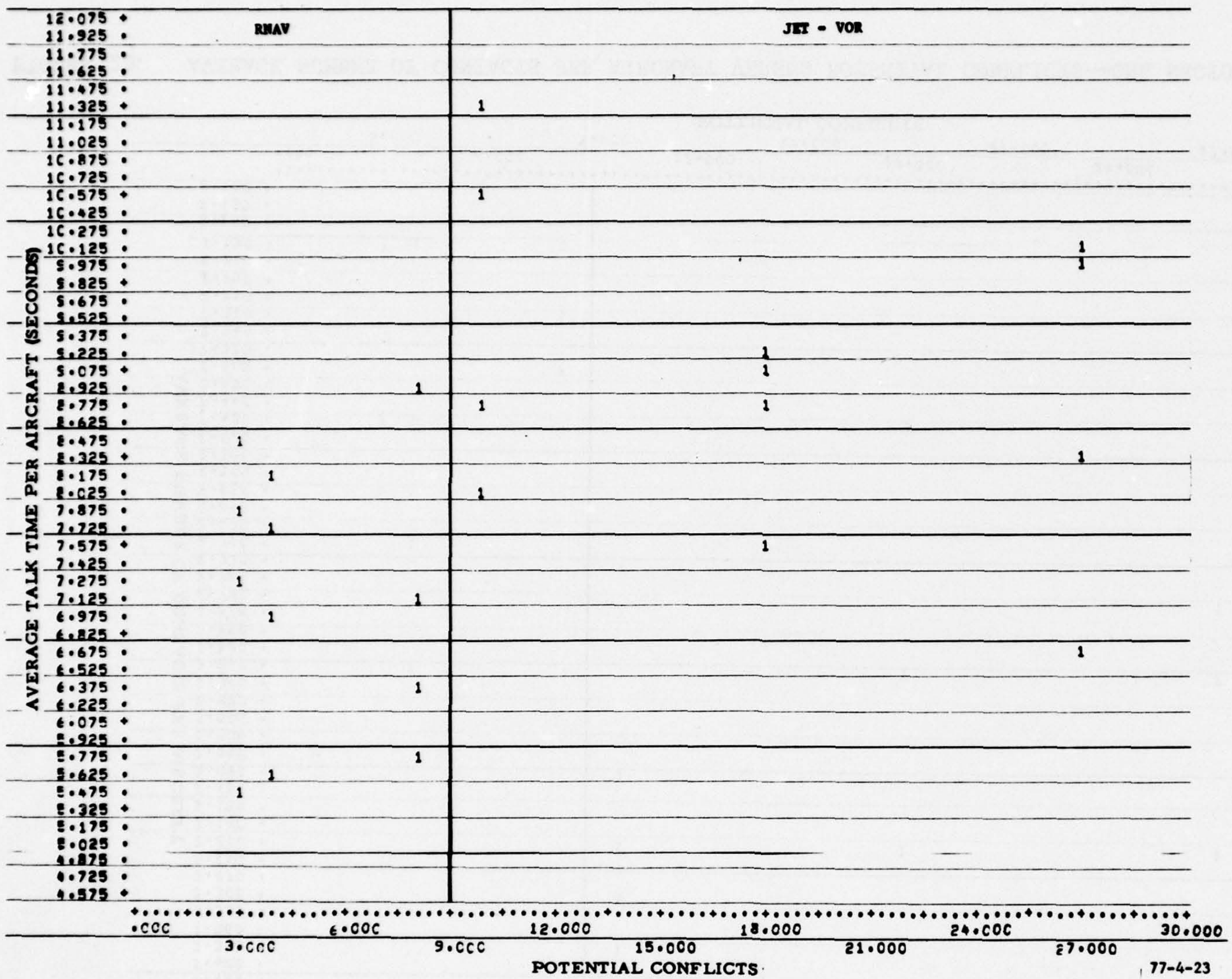

FIGURE 21. NUMBER OF CONTROL MESSAGES VERSUS POTENTIAL CONFLICTS--ONE SECTOR

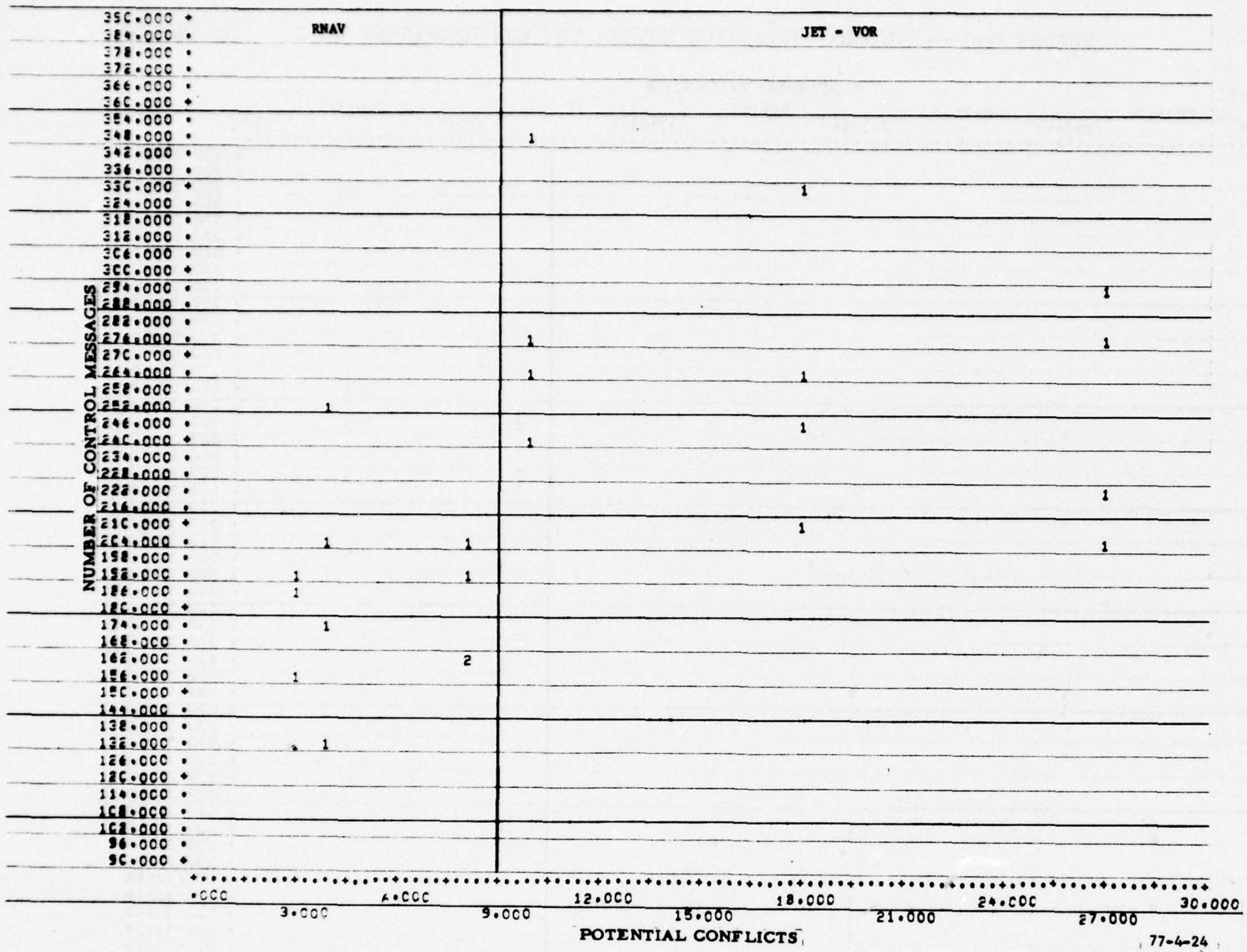

FIGURE 22. AVERAGE TALK TIME PER AIRCRAFT VERSUS POTENTIAL CONFLICTS--ONE SECTOR

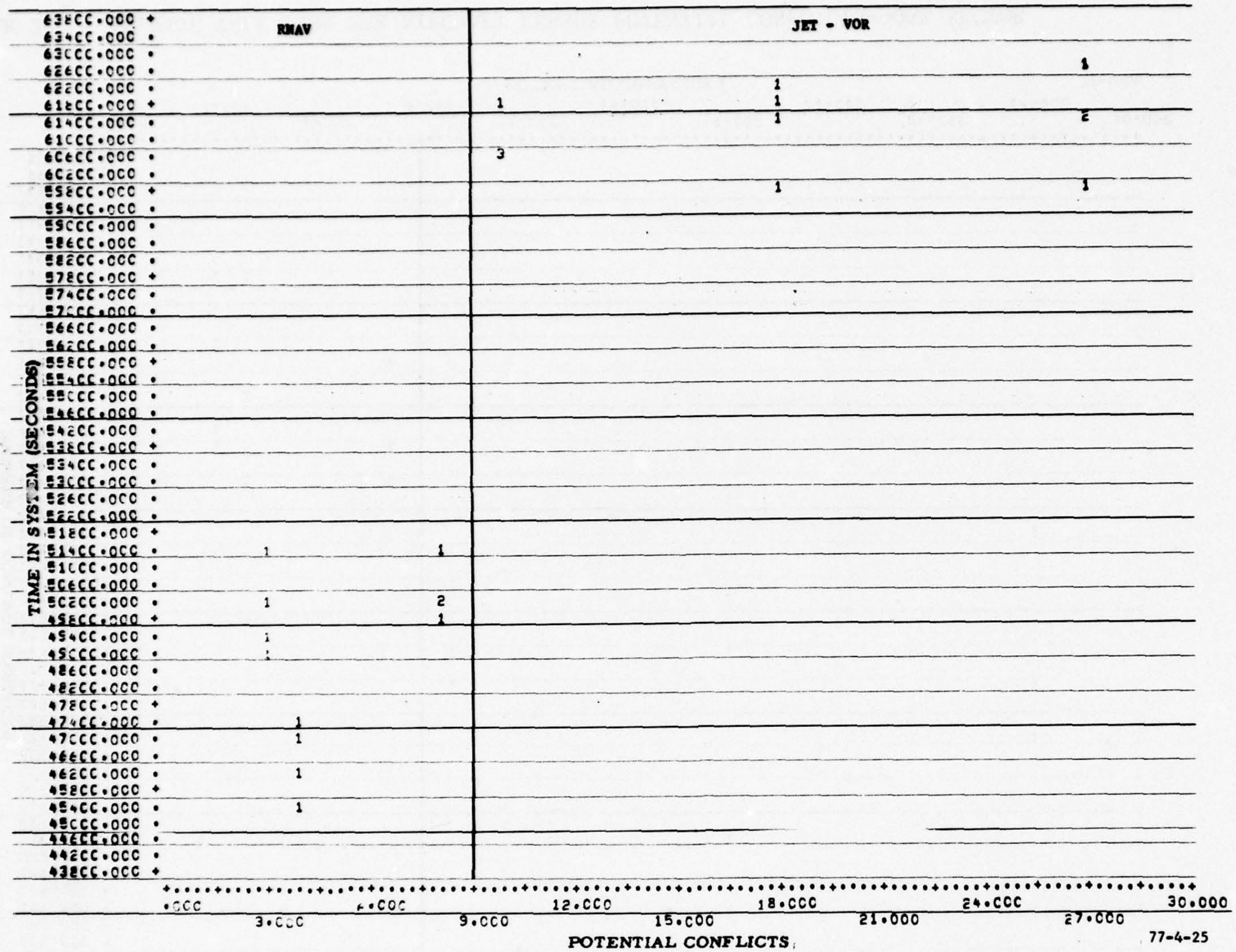

FIGURE 23. TIME-IN-SYSTEM PER RUN VERSUS POTENTIAL CONFLICTS--ONE SECTOR

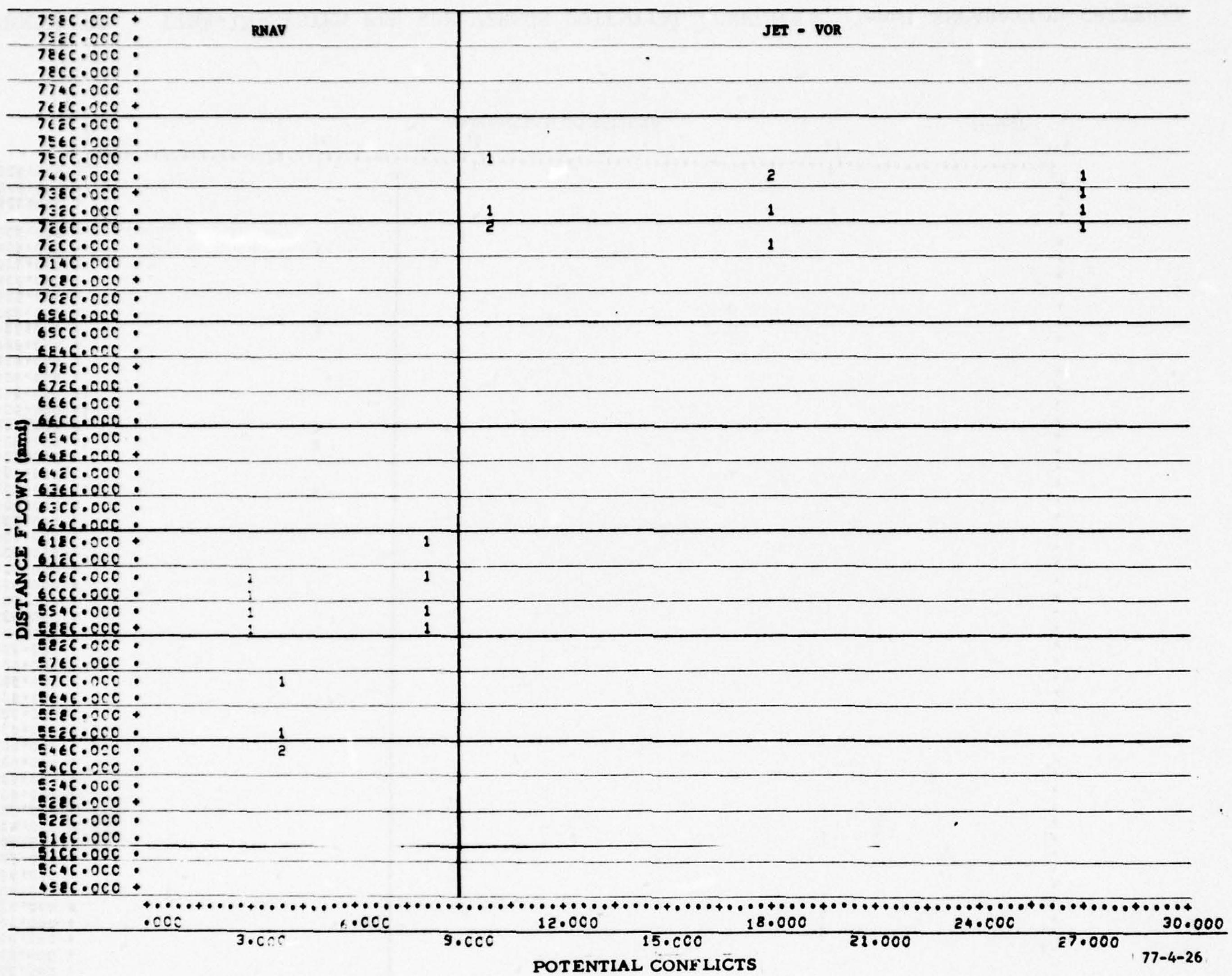

FIGURE 24. DISTANCE FLOWN PER RUN VERSUS POTENTIAL CONFLICTS—ONE SECTOR

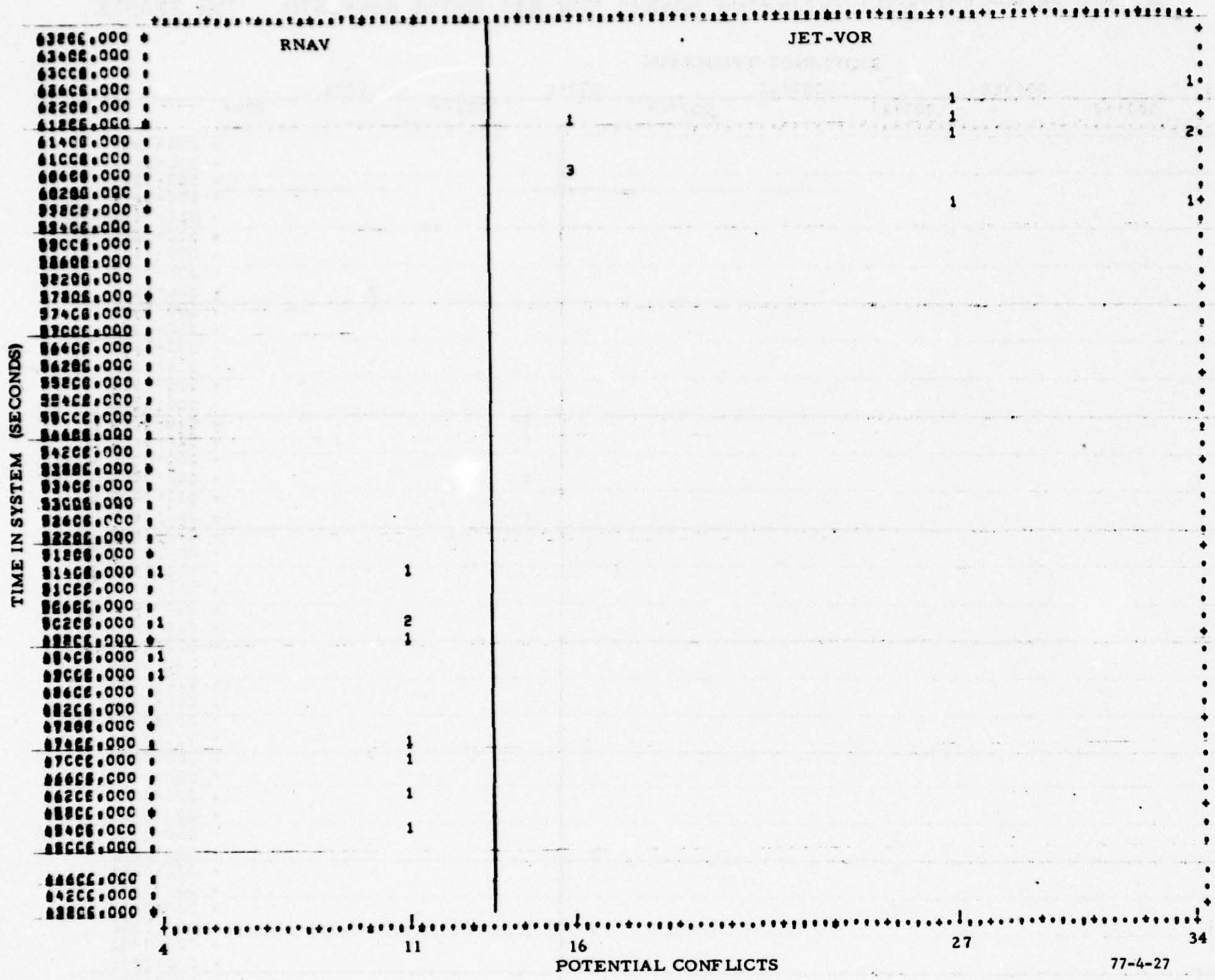

FIGURE 25. TIME-IN-SYSTEM PER RUN VERSUS POTENTIAL CONFLICTS, 7-nmi SEPARATION CRITERIA

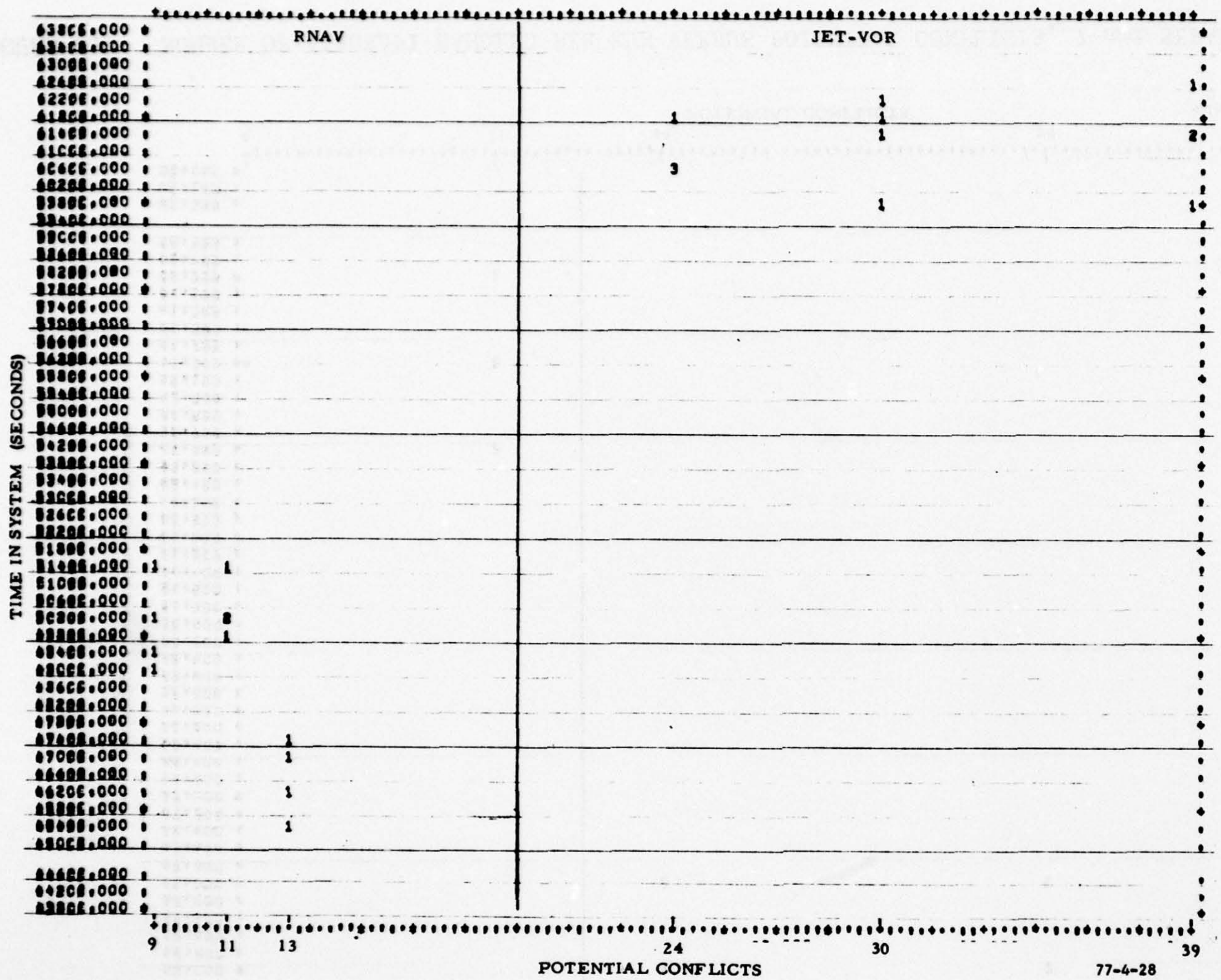

FIGURE 26. TIME-IN-SYSTEM PER RUN VERSUS POTENTIAL CONFLICTS, 10-nmi SEPARATION CRITERIA

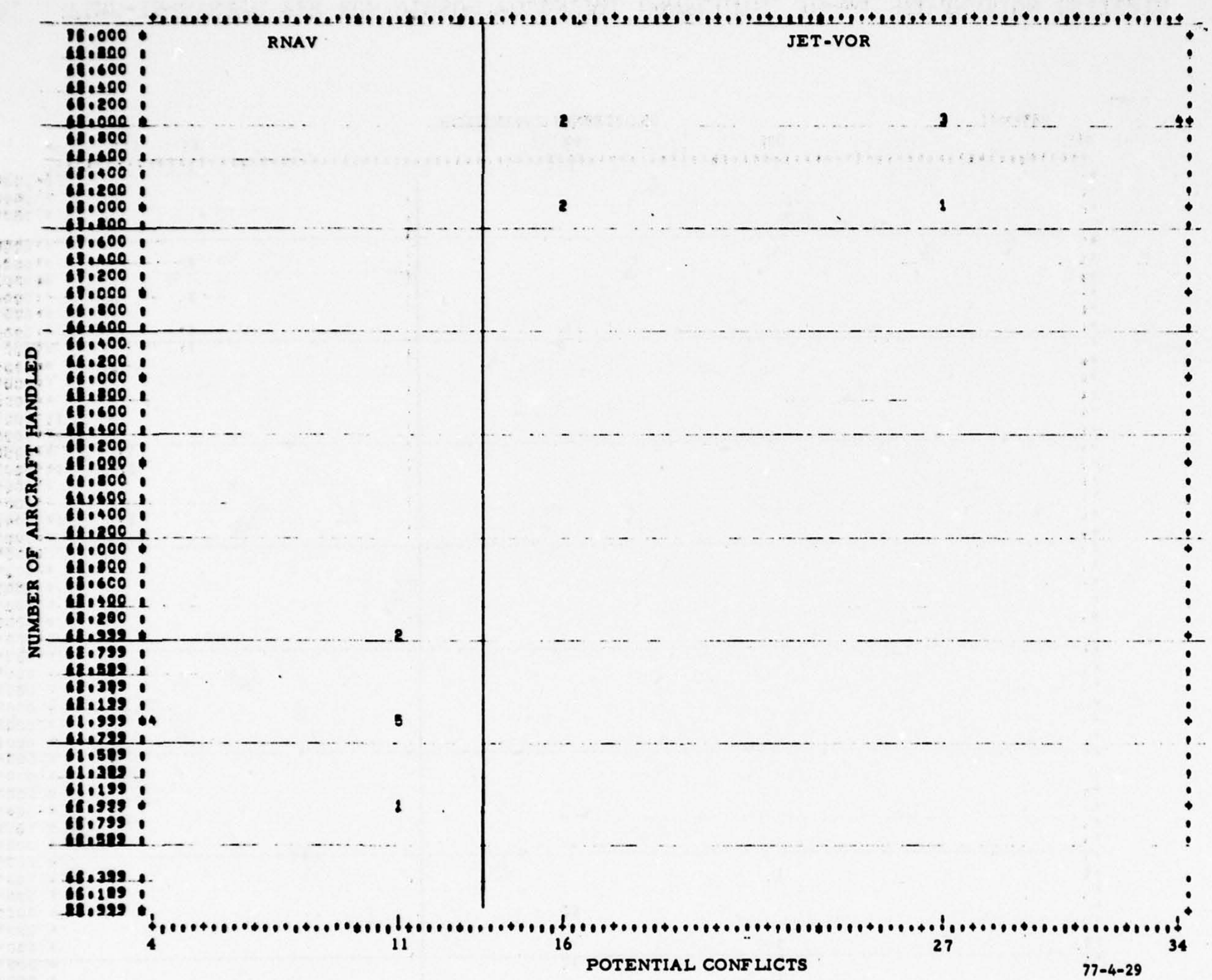

FIGURE 27. NUMBER OF AIRCRAFT HANDLED PER RUN VERSUS POTENTIAL CONFLICTS, 7-nmi SEPARATION CRITERIA

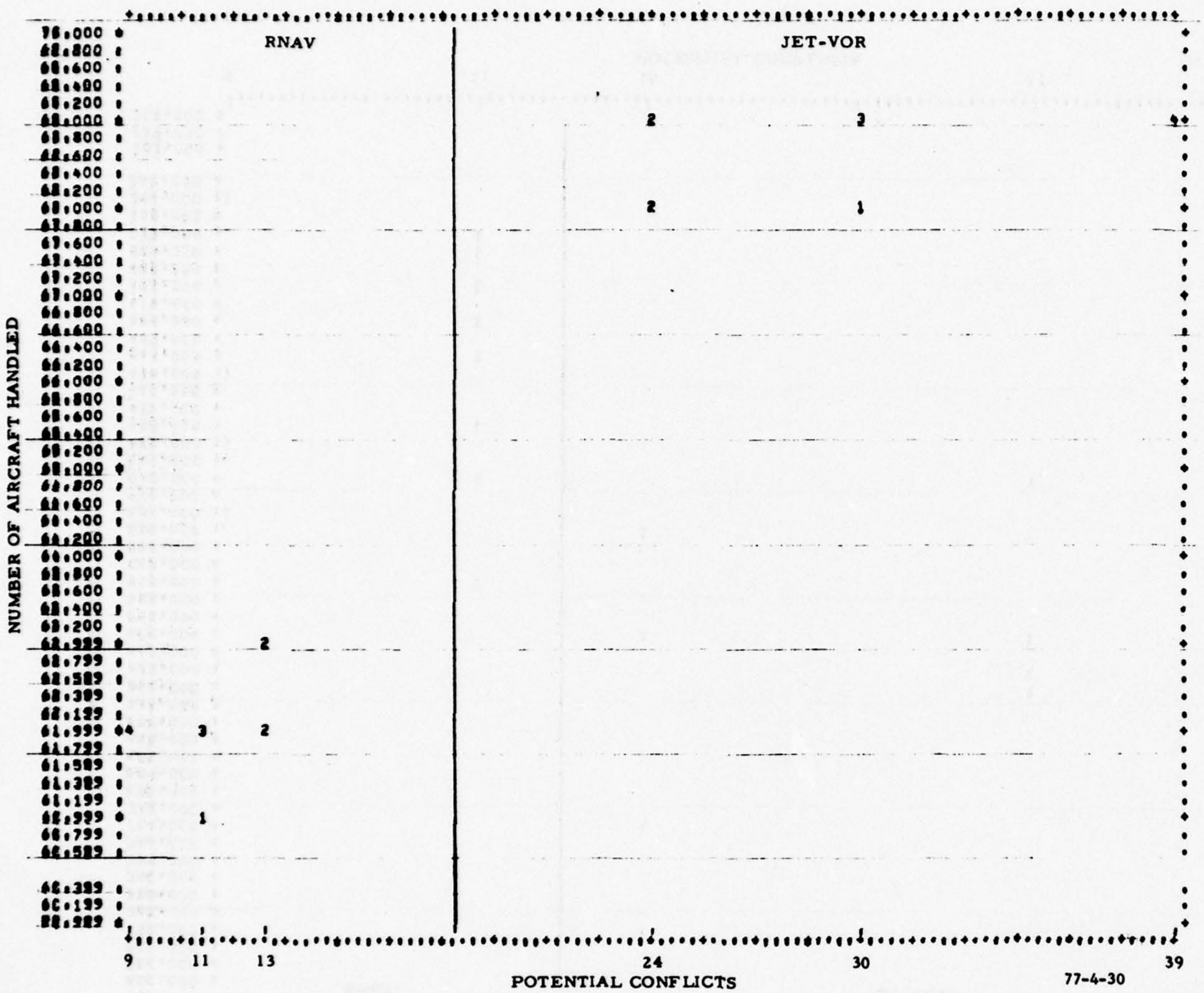

FIGURE 28. NUMBER OF AIRCRAFT HANDLED PER RUN VERSUS POTENTIAL CONFLICTS, 10-nmi SEPARATION CRITERIA

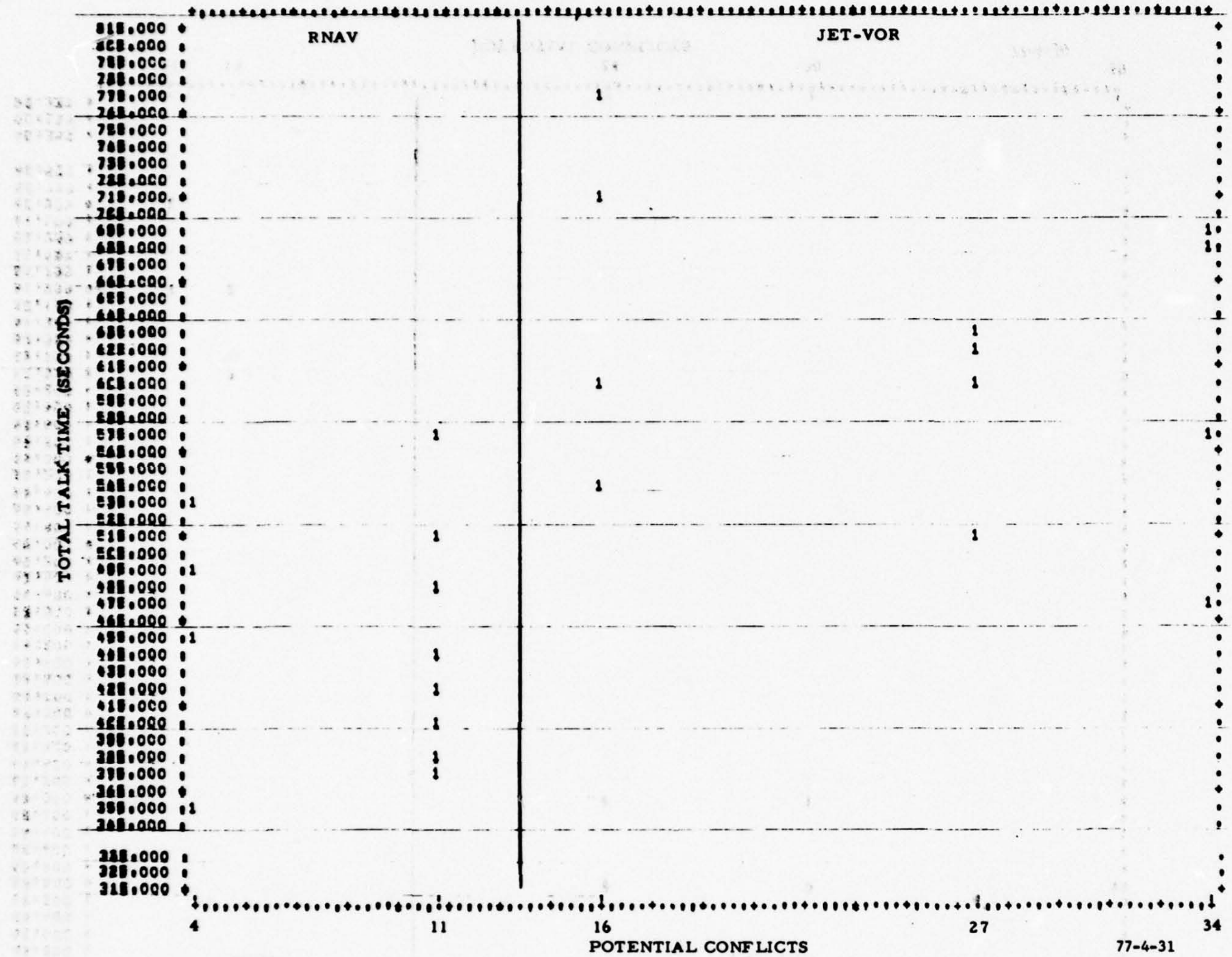

FIGURE 29. TOTAL TALK TIME PER RUN VERSUS POTENTIAL CONFLICTS, 7-nmi SEPARATION CRITERIA

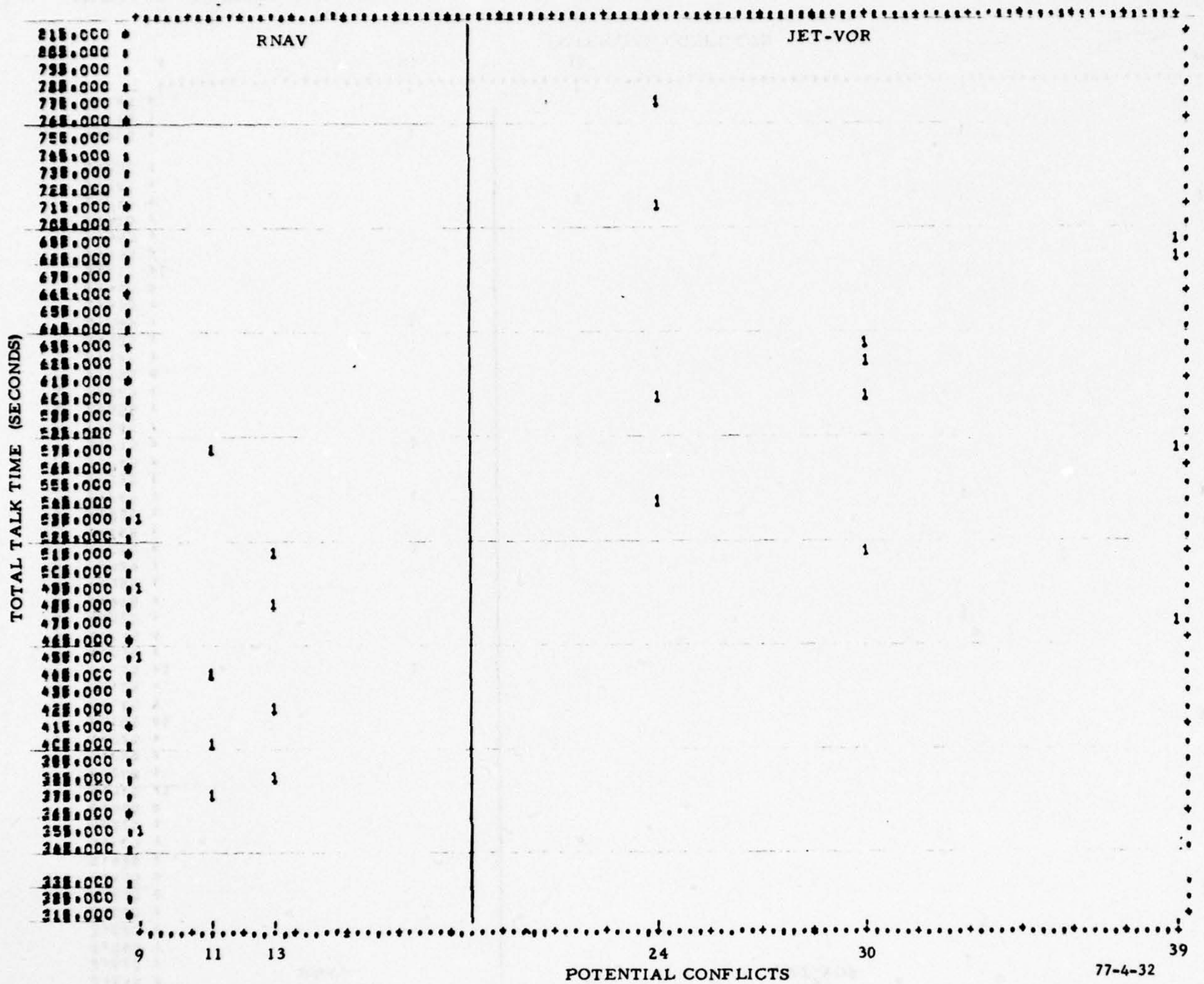

FIGURE 30. TOTAL TALK TIME PER RUN VERSUS POTENTIAL CONFLICTS, 10-nmi SEPARATION CRITERIA

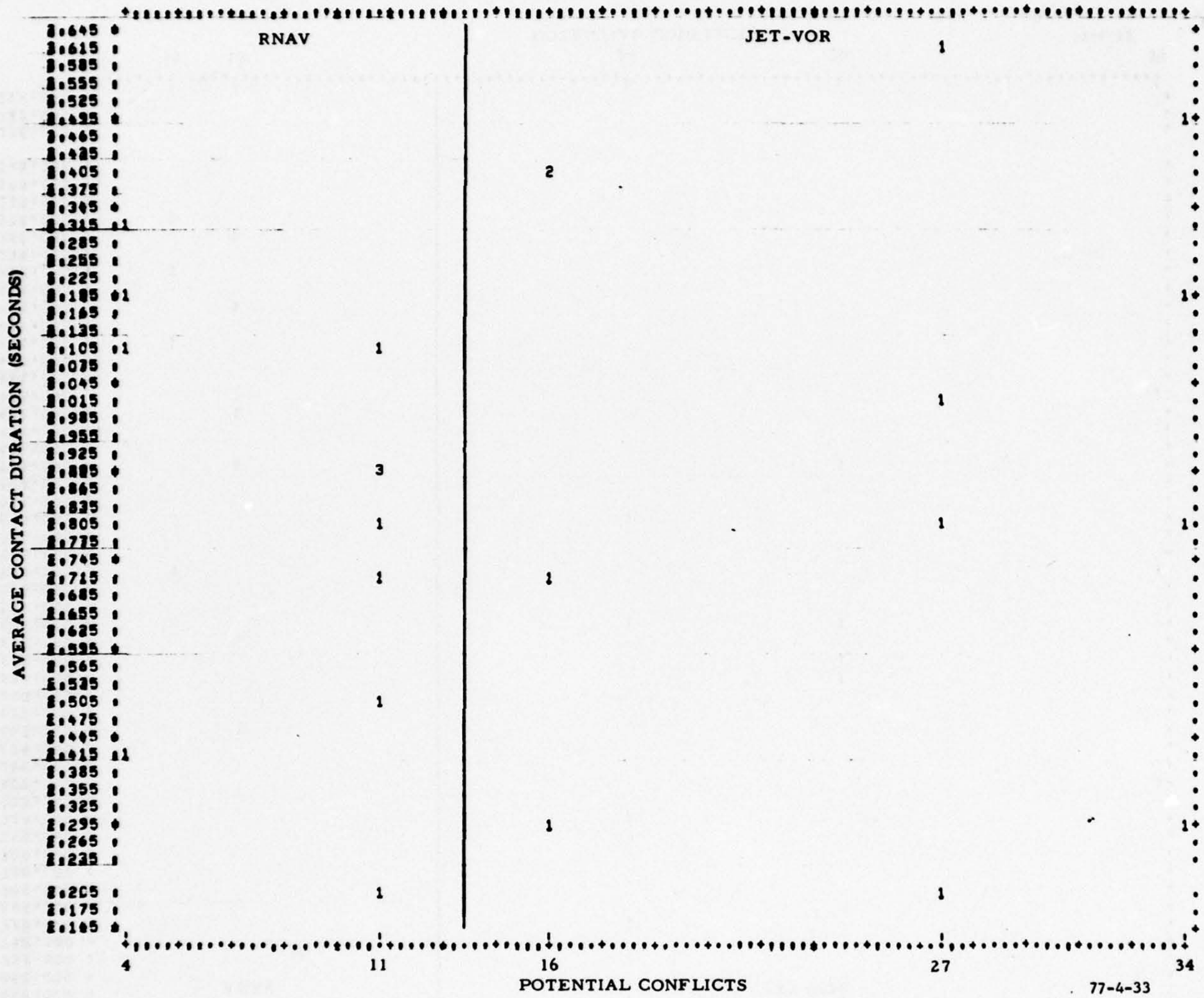

FIGURE 31. AVERAGE CONTACT DURATION PER RUN VERSUS POTENTIAL CONFLICTS, 7-nmi SEPARATION CRITERIA

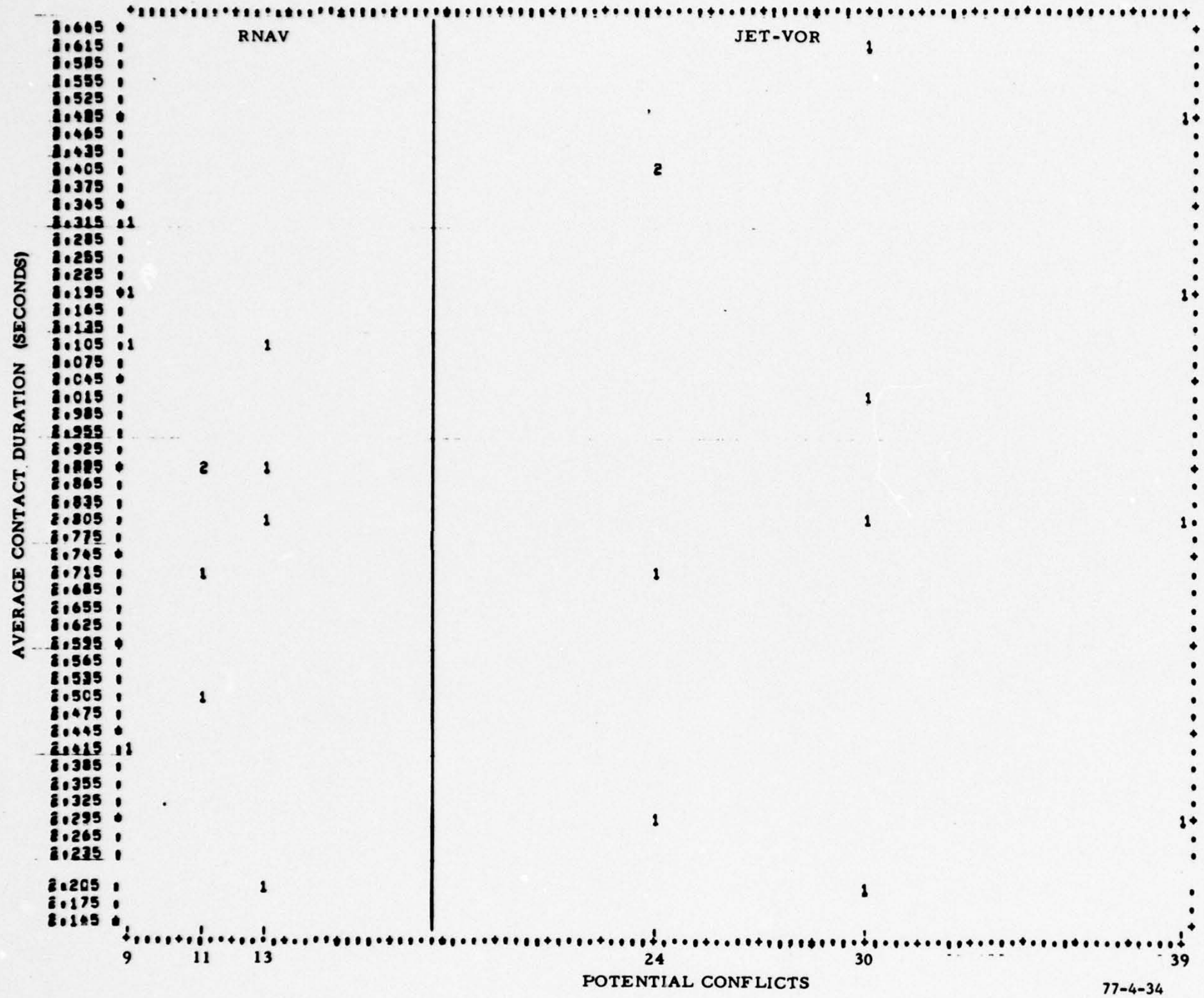

FIGURE 32. AVERAGE CONTACT DURATION PER RUN VERSUS POTENTIAL CONFLICTS, 10-nmi SEPARATION CRITERIA

APPENDIX A

REDUCTION OF LINCOLN LABORATORY DATA TAPES/HIGH-ALTITUDE RNAV TRAFFIC SAMPLE SELECTION

The Lincoln Laboratory data tapes covered a 26-hour period and accounted for some 14,574 aircraft flights in the continental United States. These flights operated both in the low- and high-altitude strata.

Selected high-altitude sectors of the Chicago (CHI) ARTCC comprised the simulated area with associated geography and aircraft density obtained from data tapes developed by Lincoln Laboratory. These base data also accounted for routing, fix data, type of flights (i.e., departures, arrivals, and overflights), and type and weight of aircraft, which determined aircraft category for both RNAV and Jet-VOR samples. Aircraft category was used to determine the aircraft's maneuvering profile for rates of climb, descent, turn, indicated airspeed, etc.

Shown in figure A-1 is the method used to process the Lincoln Laboratory data tapes to the DSF computer format and select the routes that entered and departed the CHI ARTCC's area. To reduce the number of computer records used to store the selected route data of the Jet-VOR and RNAV systems, points along an arbitrary arc of 450-nmi radius from Chicago were used as the starting points for the selected entry routes which originated outside this arc.

After the selection of the Jet-VOR and RNAV routes (that entered the five-sector test area) was made, the data were processed further to identify routes that were matched pairs (considering origin and destination (figure A-2). Only paired routes that served both system were selected for the simulation tests. Those routes that were eliminated were nonetheless sorted on tapes for further consideration. After ascertaining the specifics of the test program, it was discovered that the traffic density was too low to be representative of traffic that would be realistic for controller activity. To overcome this, 13 Jet-VOR routes (that entered the test area without paired RNAV routes) were introduced as RNAV routes for the RNAV tests.

No RNAV routes were substituted into the Jet-VOR system. The rationale being that RNAV-equipped aircraft can navigate in a Jet-VOR route system while VOR-equipped aircraft cannot navigate in a RNAV route system.

For the one-sector configuration tests, a selection of routes that entered the test sector was made from the five-sector traffic sample. Also deleted were departure routes from the Chicago terminal area that cut across the corners of the single-sector test. This traffic would be vectored by the terminal controller around the corners prior to handoff to the receiving adjacent sector controller and was not controlled by the single-sector controller during the five-sector tests. The elimination of this corner traffic had no effect on the number of potential conflicts for the test sector.

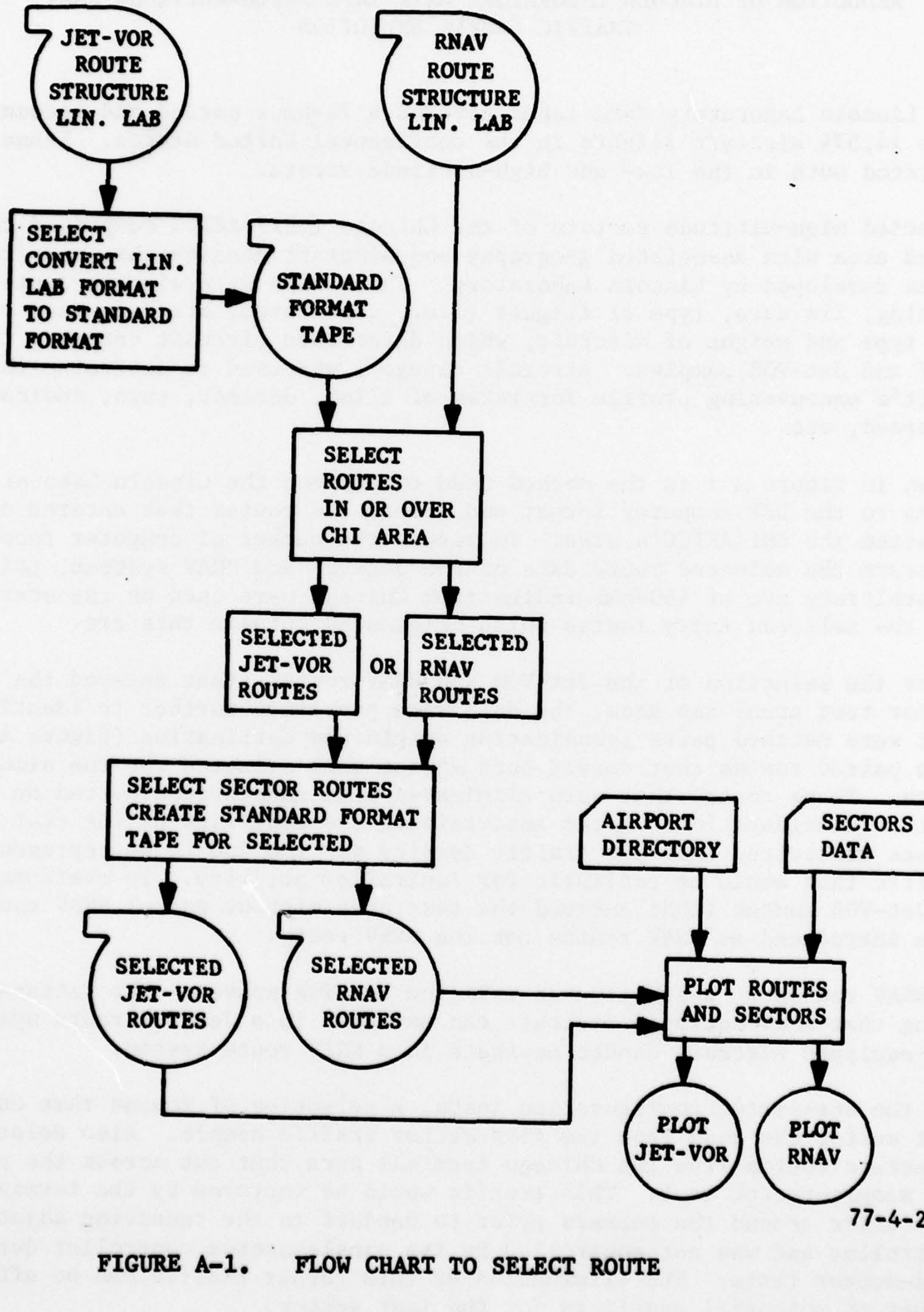

FIGURE A-1. FLOW CHART TO SELECT ROUTE

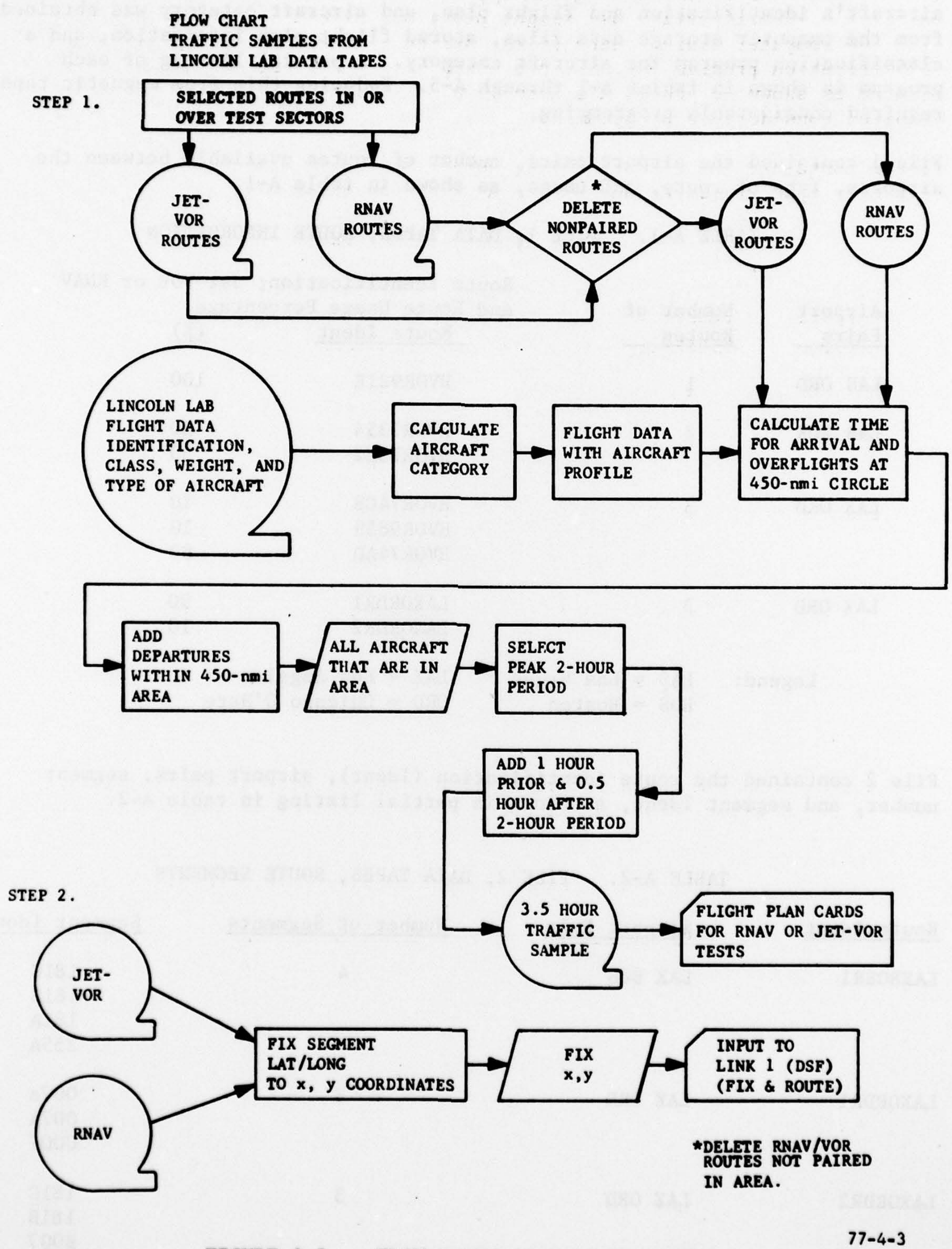

FIGURE A-2. FLOW CHART OF TRAFFIC SAMPLE

The construction of the area geometry, route loading, route segments, fixes, aircraft's identification and flight plan, and aircraft category was obtained from the computer storage data files, stored flight plan information, and a classification program for aircraft category. A partial listing of each program is shown in tables A-1 through A-5. Reducing this from magnetic tapes required considerable programming.

File 1 contained the airport pairs, number of routes available between the airports, type of route, and usage, as shown in table A-1.

TABLE A-1. FILE 1, DATA TAPES, ROUTE INFORMATION

Airport Pairs	Number of Routes	Route Identification; Jet-VOR or RNAV and Route Usage Percentage: Route Ident	(%)
LAS ORD	1	HVOR921E	100
LAS BOS	2	HVOR7354	50
		HVOR7322	50
LAX ORD	3	HVOR74C8	10
		HVOR9859	10
		HVOR74AD	80
LAX ORD	2	LAXORDR1	90
		LAXORDR2	10

Legend: LAS = Las Vegas, BOS = Boston, LAX = Los Angeles, ORD = Chicago O'Hare

File 2 contained the route identification (Ident), airport pairs, segment number, and segment Ident, as shown in partial listing in table A-2.

TABLE A-2. FILE 2, DATA TAPES, ROUTE SEGMENTS

Route Ident	Airport Pair	Number of Segments	Segment Ident
LAXBOSR1	LAX BOS	4	181C
			181B
			181A
			255A
LAXORDR1	LAX ORD	3	007a
			007A
			C007
LAXORDR2	LAX ORD	3	181C
			181B
			E007

File 3 contained the latitude and longitude for the start and end fix of each segment, segment length in nautical miles, number of route segments, and route Ident. Shown in table A-3 is a partial listing of file 3. The start and end points defined fixes used in the routes. A program changed latitude/longitude data to Cartesian rectangular coordinates x and y.

TABLE A-3. FILE 3, DATA TAPES, FIX LOCATIONS, AND SEGMENT LENGTH

Segment Ident	North Lat	West Long	North Lat	West Long	Length (nmi)	Common Route Segments	Route Ident
E007	414221	891108	413954	903224	60.86	1	LAXORD2
D366	410057	881501	400219	883131	59.96	1	MEMORDR1
P005	421857	890955	424215	9025122	60.37	2	MDWSFOR1 ORDSFO3

After applying the same algorithm as Lincoln Laboratory, aircraft were assigned to the selected routes. Table A-4 shows a partial listing of the flight plan information.

TABLE A-4. FLIGHT PLAN INFORMATION

Flight Ident.	User	Type	True Air-speed (knots)	Dept Arpt	Alt ft x 100	Arr Arpt	Spl Equip	Pro-posed Time	Weight (lbs)	No
N119K	GA	G159	490	OAK	230	LGA	C	1900	35,100	9867
TW118C	AC	CV88	477	OAK	330	ORD	C	1630	184,500	9870
UA232	AC	B727	460	OAK	330	ORD	C	1830	153,000	9871

User is by type: GA, general or civil; AC, air carrier; M, military

Spl Equip is the type of transponder aboard the aircraft. C is 4096 code capability transponder.

No. is the Lincoln Laboratory flight plan number.

The next step was to determine the aircraft category for each flight. The aircraft category selected the appropriate aircraft's operating profile used by the DSF programs. Shown in table A-5 is the method used to classify aircraft into categories. Had the tests included the low-altitude stratus, a minimum of 37 aircraft categories would have been required.

TABLE A-5. METHOD TO CLASSIFY AIRCRAFT CATEGORY

Engine(s)	Weight (lb)	User	Category
S, M	> 6,500	GA	1, 2, 3
	≤ 60,000	AC	2
M	> 60,000	AC	4, 5, 6
	≤155,000	GA	
M	>155,000	AC	7, 8, 9
	≤300,000	GA	
M	>300,000	AC	10, 11, 12
		GA	

For this simulation 12 aircraft categories were used. Rather than increase the number of categories so that each aircraft had its own profile, arrival and overflight aircraft entered the problem at filed true airspeed rather than profile speed. This program change of profile cruise speed to filed speed gave each aircraft its own true airspeed. Departure flights reaching cruise altitude (filed in flight plan) would cruise at filed true airspeed. Thus, computer core space was available for other programs.

Using the aircraft profile assigned by category, a computer program calculated the aircraft's time at the 450-nmi-radius arc from CHI. From here, the aircraft were advanced to the fix prior to the sector boundary. This fix then became the start point. The time at the start point was used by the DSF computer program to activate the aircraft in the simulation tests. This accounted for all arrival and overflights that would operate within the five sectors of interest. Added to those flight were the departures within the five sectors.

To insure high traffic density, a computer program was used to determine the peak 2 hours. Added were aircraft that would enter the area 1 hour prior to, and 1/2 hour after this peak period. This then became the master traffic sample. Figure A-2 defines the events and is shown under step 1.

After the selection of Jet-VOR and RNAV routes for the test area, a delete function was made for routes which had no equivalent (paired) Jet-VOR or RNAV route. Since there were more Jet-VOR routes without a paired RNAV route, it was necessary to use a few of the Jet-VOR routes (approximately 13) in the RNAV route system to insure sufficient traffic density in both system tests. The rationale for using the Jet-VOR route system was that RNAV-equipped aircraft can navigate on a VOR route while the opposite cannot be done.

Shown in figure A-2, step 2, was the method to modify the geographical data for use in the DSF programs.

APPENDIX B

TRAFFIC SAMPLE COMPOSITION

Shown in table B-1 is the general composition of aircraft flights that operated in the Jet-VOR and RNAV tests for the five- and one-sector simulations. The tabulation depicts airport operations (arrivals, departures, and within) and overflights. The airports listed are in the test area or adjacent to the test area. Adjacent airports' operations are summarized for departure flights only. Within flights are those that departed an airport in the test area or an adjacent airport and arrived at an airport within the test area. Within flights are accounted for by departure airport with the destination airport shown next to the operation count. The operations for Midway and O'Hare airports are itemized for departures and arrivals, since these airports generated a majority of the test area's traffic. Overflights are flights which did not depart or arrive at an airport in the test area.

TABLE B-1. MATRIX FOR SAMPLES

		Five Sectors		
Airport	Arrivals	Departures	Within	Overflights
Cedar Rapids (CID)	2	2	1-ORD	122
Des Moines (DSM)		2	2-ORD	
Dubuque (DBQ)	1	1		
Midway (MDW)	9	3		
Milwaukee (MKE)	4	5		
O'Hare (ORD)	53	89	3-CID	
Peoria (PIA)	2			
Total	71	102	6	122

		One Sector		
Airport	Arrivals	Departures	Within	Overflights
Cedar Rapids (CID)			1-ORD	26
Des Moines (DSM)		1	2-ORD	
Dubuque (DBQ)	1	1		
Midway (MDW)	4	2		
Milwaukee (MKE)		3		
O'Hare (ORD)	13	23	3-CID	
Total	18	30	6	26

Note: The above matrices for traffic samples are a summary of total count of aircraft operations which includes: buildup, data, and end periods. Shown in figure 1 is the location of each airport.

APPENDIX C

RECORDED DATA PER RUN

The data in tables C-1 and C-2, appendix C, are summaries. There are four types of routes; enroute, transition, approach, and final. The item recorded under routes would record the type of route that the aircraft was on. Table C-1 contained 19 items, and table C-2 contained 54 items.

TABLE C-1. DATA RECORDED PER RUN

1. Route--type of route
2. Fixes--x and y coordinates, name, type
3. Problem start time in seconds
4. Common areas between digital displays
5. Number of digital displays.

TABLE C-2. DATA RECORDED PER SECOND

1. Time in seconds--reference to 24-hour clock
2. Largest number of aircraft at any one time in test area
3. Communication lines--number, duration and block time
4. x, y, and z, i.e., aircraft's grid coordinates and attitude
5. Aircraft heading--radians
6. Desired climb and descent rate, feet per second
7. Next fix--x,y--aircraft homing
8. Last offset point (x,y), aircraft on offset
9. Next offset point (x,y), aircraft on offset
10. Offset distance--nautical miles
11. RNAV status--aircraft enroute simulation are similar to,
12. RNAV equipment code
13. Crossing-altitude restrictions--route or clearance
14. Previous altitude assigned
15. Station VOR or fix--x,y
16. Measured x,y from station or fix
17. Groundspeed, nautical miles per second
18. Aircraft identification--call sign
19. Aircraft turn rate--radians of change per second
20. Aircraft speed delay--seconds prior to speed change
21. Aircraft heading delay--seconds prior to heading change
22. Aircraft altitude delay--seconds prior to altitude change
23. Desired heading turning to--radians
24. Indicated airspeed--nautical miles per second
25. Bearing to next fix--radians
26. Distance to next fix--nautical miles
27. Last fix and next fix--x,y coordinates
28. Aircraft tracking x,y,z as determined by radar sweep
29. Climb rate--feet per second per second
30. Acceleration/deceleration rate--nautical miles per second per second
31. Desired speed--airspeed change--nautical miles per second
32. Aircraft status--in or out of problem, turning, climbing, accelerating, etc.
33. Flight plan indicator-aircraft's position
34. Aircraft type--B707, etc.
35. Requested altitude--reference from flight plan
36. True airspeed--nautical miles per second
37. Pilot number/simulator number cross reference--simulator number assigned to each flight usually by lowest entry first, etc.
38. Controller/pilot assignment
39. Pilot/controller messages--control messages by type (turn, climb, etc.) issued by each controller
40. Pilot number per aircraft--instantaneous count of aircraft assigned to each pilot.

APPENDIX D

USE OF A PERMUTATION DISTRIBUTION OF x FOR TESTING IF AN ADDITIONAL SAMPLE POINT IS A MEMBER OF A PRIMARY SAMPLE DISTRIBUTION

Reference 3 (page 489) demonstrates that the sample statistic

$$w = \frac{n_1 (\bar{X}_1 - \bar{X}_2)^2}{n^2 S^2} \quad (1)$$

where:

n_1 = Size of sample 1

n_2 = Size of sample 2

X_1 = Average for sample 1

X_2 = Average for sample 2

S^2 = Variance for the combined samples

is distributed

$$w = \frac{1}{1 + \frac{n-1}{t^2}} \quad (2)$$

where:

$n = n_1 + n_2 = n_1 + 1$

t = Students' t values for n-2 degrees of freedom

For this application, the combined sample variance S can be expressed in terms of the primary sample variance and the value for the additional point.

$$(n+1)S^2 = \sum_{i=1} X_i^2 + Y^2 - \frac{(\sum_{i=1}^{n} X_i + Y)^2}{n+1} \quad (3)$$

where:

S_1^2 = Variance of the primary sample

n = n_1

Y = X_2 = Additional sample point

X_1 = Members of primary sample

Equation 3 can be reduced to

$$(n+1)S^2 = nS_1^2 + \frac{n}{n+1} (X-Y)^2 \tag{4}$$

Solving (2) for t yields

$$t^2 = \frac{(n-1)w}{1-w} \tag{5}$$

Substituting (1) and (4) into (5) gives

$$t = \frac{\overline{X} - Y}{S_1} \sqrt{\frac{n-1}{n+1}}$$

This value can be used to test the hypothesis that the additional point Y can be considered as a member of the same parent distribution in which the primary sample, X, was driven.